# The Mediterranean Region under Climate Change

## A Scientific Update

AllEnvi
Alliance nationale de recherche pour l'Environnement

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AllEnvi, *the French National Alliance for Environmental Research*, is tasked with making the great environmental transitions work, coordinating French research into major societal issues such as food, water, climate and territories. AllEnvi i) sets policy guidelines and research priorities for advance planning before approaching funding agencies, ii) supports the emergence and structuring of research organizations, iii) coordinates innovation and technology transfer policies between public research operators, businesses and industries, and iv) contributes to the European research environment and international programme development.

Alliance nationale de recherche pour l'environnement, AllEnvi coordonne la recherche française sur les enjeux des grands défis sociétaux que sont l'alimentation, l'eau, le climat et les territoires pour réussir les grandes transitions environnementales. AllEnvi i) définit les orientations et priorités de recherche pour la programmation à l'amont des agences de financement, ii) soutient l'émergence et la structuration d'infrastructures de recherche, iii) coordonne les politiques d'innovation et valorisation entre opérateurs publics de la recherche, entreprises et industries, et iv) participe à l'Europe de la recherche et favorise l'émergence de programmes internationaux.

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# Preface

*Hakima El Haité*
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The wave of multi-faceted crises we have experienced in recent years – both in the North and in the South – offer a salutary reminder of the risks of underestimating the climate crisis. Protecting the environment is not a luxury. The message from the scientific community is loud and clear: if humanity does not change its development model, fast, life itself will be under threat. In both the North and the South – and in particular in the Mediterranean region.

Every page of this book, written by some of the top specialists in the field on either side of the Mediterranean, reminds us of this. Beyond the blue sea and the beauty of the beaches, the Mediterranean is suffering. In fact, few regions in the world are as affected by climate change.

Which explains the purpose of bringing together, for the first time, the most recent findings on climate change in the Mediterranean regions. This book and toolkit will offer all those variously involved in decision-making on environmental policy in the Mediterranean and beyond a better understanding of our shared ecosystem. This innovative and cross-cutting approach to the fragility and the challenges facing Mediterranean peoples requires the development of a global integrated strategy.

What is true on a regional scale is also true on a planetary scale.

The Paris Accords signed on 12 December 2015 signalled a robust response to these demands from the international community, and heralded developments that were unprecedented in the struggle against climate change: for the first time, 195 countries from both the North and the South came together to proclaim the need to engage the whole of humanity in a global energy transformation. That proclamation must now be turned into action. Nothing less than a paradigm shift is called for. From all of us.

In welcoming the 22nd Conference of the Parties to Marrakesh from 7-18 November 2016, and in labelling this the 'COP of action', the Kingdom of Morocco is committed to implementing the Paris Accords.

The size of the task facing the COP 22 is, as we all know, immense. It means adopting the procedures and mechanisms to turn the Accords into a reality, drafting a plan of action for the pre-2020 period in terms of mitigation, adaptation, funding, capacity building, technology transfer and transparency, particularly in favour of the most vulnerable countries, such as the small developing island nations and the least developed countries.

To this end, our country will channel all its experience and expertise in the field. Since 2009, His Majesty King Mohammed VI has taken our country forward along the path towards sustainable economic development and global energy transformation – thus demonstrating remarkable leadership on the African continent and beyond. The whole of Africa, rich in youth and resources, has enormous potential. We must give it the support it needs to become an example of sustainable development for us all.

Our country intends to show the whole world that, even in a region as vulnerable to global warming as the Mediterranean, adapting to the environment is possible, particularly through the introduction of a sizeable renewable energy programme. Our considerable experience in the matter has already inspired a number of convictions about our shared mission: the energies mobilised by countries in the fight against climate change involve all of us, and in particular non-governmental actors, from civil society to the private sector, and from regional authorities to the media.

It is only through the firm commitment of every stakeholder to reducing greenhouse gas emissions to 2°C and ultimately to 1.5°C that we will turn back the tide of history. The task that lies before the actors at the COP 22 in Marrakesh is to prove the efficacy of measures taken in the North and the South to adapt to and mitigate the effects of climate change.

But there can be no effective solutions and innovations without research upstream. And there can be no research without reliable data. With its overview of current research in the Mediterranean, this book provides decision-makers with indispensable tools, which can be used to implement political action and outline those areas in which research must continue as a matter of priority. For there to be a solution a clear diagnosis and objectives are crucial.

It is through the joint efforts of all in Marrakesh – researchers and engineers, industrialists and farmers, elected representatives and CEOs – that we will breathe life into the paradigm shift of the Paris Accords, in order to witness the birth – in both the North and the South – of a new model of sustainable development able to ensure the economic and social wellbeing of all.

# Préface

*Hakima El Haité*
Ministre déléguée auprès du Ministre de l'Energie, des Mines, de l'Eau et de l'Environnement, chargée de l'Environnement.
Championne de haut niveau du Maroc pour le climat

Les crises successives et multidimensionnelles que nous vivons depuis plusieurs années, au Nord comme au Sud, nous rappellent les risques qu'il y aurait à sous-évaluer la crise climatique. Protéger l'environnement n'est pas un luxe. A cet égard, le message de la communauté scientifique est sans appel : la vie des générations futures sera définitivement menacée si l'humanité ne change pas rapidement son modèle de développement. Au Nord comme au Sud. Et en particulier dans la région méditerranéenne.

Car cet ouvrage, élaboré par certains des meilleurs spécialistes de ces questions sur les deux rives de la Méditerranée, nous le rappelle à chaque page : derrière le bleu de la mer et la beauté des plages, la Méditerranée souffre. C'est même l'une des régions du monde les plus impactées par le changement climatique.

D'où l'utilité de rassembler pour la première fois l'état des connaissances les plus récentes sur le changement climatique dans les régions méditerranéennes. Ce livre – outil de travail – permettra à celles et ceux qui exercent, à des degrés divers, des responsabilités en matière de politiques environnementales dans l'espace méditerranéen et au-delà de mieux appréhender l'écosystème commun dans lequel ils évoluent. Cette approche innovante transversale de la fragilité et des défis auxquels font face les populations méditerranéennes implique en retour de les gérer à partir d'une stratégie globale et intégrée.

Ce qui est vrai à l'échelle régionale l'est aussi à l'échelle de la planète.

Signé le 12 décembre 2015, l'Accord de Paris a constitué une réponse forte de la communauté internationale à cette exigence. Et une avancée sans précédent dans l'histoire de la lutte contre le changement climatique : pour la première fois, 195 pays, du Nord comme du Sud, ont affirmé d'une même voix la nécessité d'engager l'humanité dans une transformation énergétique globale. Une promesse qu'il faut désormais transformer en actes. Un changement de paradigme à construire. Collectivement.

En accueillant du 7 au 18 novembre 2016, la 22e Conférence des Parties à Marrakech et en annonçant au monde que la COP 22 serait la « COP de l'action », le royaume du Maroc s'est engagé au service de la mise en œuvre de l'Accord de Paris.

Le chantier de la COP 22, nous le savons, est immense, puisqu'il s'agit d'adopter les procédures et mécanismes d'opérationnalisation de l'Accord, de définir un plan d'action pour la période pré-2020 en termes d'atténuation, d'adaptation, de financement, de renforcement des capacités, de transfert de technologie et de transparence, en particulier en faveur des pays les plus vulnérables, notamment les petits États insulaires en développement et les pays les moins avancés.

Pour y parvenir, notre pays mobilisera son expérience et son savoir-faire acquis en la matière. Depuis 2009, en effet, sa Majesté le Roi Mohammed VI a engagé notre pays dans la voie d'un développement économique durable et d'une transformation énergétique globale qui lui vaut une reconnaissance de son leadership en la matière sur le continent africain et au-delà. L'Afrique tout entière, riche par sa jeunesse et ses ressources, concentre justement d'immenses potentialités. Il faut lui donner les moyens d'être un exemple pour tous en matière de développement durable.

Notre pays entend montrer au monde entier que, même dans une région aussi vulnérable au réchauffement climatique qu'est la Méditerranée, il est possible de s'adapter à son environnement, notamment par la mise en place d'un important programme de développement des énergies renouvelables. Cette expérience considérable nous a déjà apporté certaines convictions au regard de notre mission collective : la dynamique enclenchée par les contributions nationales des pays à la lutte contre le réchauffement climatique passe au sein de chaque pays par la mobilisation de tous les acteurs en particulier les acteurs non étatiques : société civile, secteur privé, collectivités publiques, médias...

C'est par l'engagement ferme de chacun à s'inscrire dans une trajectoire de diminution des émissions de gaz à effet de serre à 2 °C tendant vers les 1,5 °C que nous réussirons à inverser le cours de l'Histoire. C'est aussi avec tous ces acteurs que la COP 22 de Marrakech pourra montrer la réalité des actions entreprises au Nord comme au Sud, en matière d'adaptation et d'atténuation face au changement climatique.

Mais il ne peut y avoir de solutions et d'innovations pertinentes sans recherche fiable en amont. Et il ne peut y avoir de recherche fiable sans données fiables. En donnant le paysage global de l'état de la recherche sur la Méditerranée, ce livre donne aux décideurs de la région les éléments indispensables à la mise en œuvre de l'action politique et la possibilité de définir les domaines où les recherches doivent être poursuivies de façon prioritaire. Il ne peut y avoir de solution sans diagnostic sûr et objectif.

C'est par la convergence des efforts de tous, chercheurs et ingénieurs, industriels et paysans, élus et chefs d'entreprise que nous donnerons vie à Marrakech au changement de paradigme de l'accord de Paris, afin que naisse, au Nord comme au Sud, un nouveau modèle de développement durable capable d'assurer le bien-être économique et social de tous.

# Introduction

## Climate change in the Mediterranean

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The Intergovernmental Panel on Climate Change (IPCC), whose work played a major role in the 'historic' agreement reached at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21) in Paris in December 2015, has shown that the Mediterranean Basin is one of the most vulnerable areas of the planet to climate change. COP 22 will take place in Marrakesh from 7 to 18 November but ahead of this event, Morocco hosted MedCOP Climate, the Mediterranean climate forum for all governmental and non-State bodies on 18 and 19 July in Tangier in order to build on the work begun during MedCOP 21 in Marseille the previous year. In his introductory speech at MedCOP 22, His Majesty Mohammed VI, King of Morocco, stressed the Mediterranean's duty to set an example by creating new consumption and production patterns and developing innovative approaches to combating climate change.

In response to a request from the Moroccan authorities, particularly Environment Minister Mrs Hakima El Haité, the 28 ALLENVI members have published a remarkable summary work for COP 22. This work aims to provide an overview of high-level scientific research on climate change, the consequences of this climate imbalance and mitigation and adaptation solutions specific to the

Mediterranean. It demonstrates the remarkable work carried out by scientists, researchers and academics on both shores of the Mediterranean to understand the mechanisms of climate change both today and in the long term, and the impact of climate imbalance on the environment, the economy, health and society. It also suggests and recommends responses based on 'scientific evidence', including adaptation, resilience, conservation of resources and risk prevention. This book is the work of a broad scientific community which has been working together for a number of years to capture the complexity of the Mediterranean situation and create the conditions for better mutual knowledge of the interlinking scientific issues that will be defined step-by-step with a view to breaking down the barriers between disciplines.

This work does not claim to be exhaustive, despite the diversity and quality of the contributions it contains. Certain key themes, such as the role of reducing greenhouse gas emissions and energy innovations in mitigation processes, are mentioned only briefly. Furthermore, certain chapters highlight the limitations of the results that have been obtained (for example the limited observations and climate simulations in the study on extreme hydrological events and the lack of long-term data on the impact of climate change on human health), revealing subjects for up-and-coming or future research.

Readers will be able to form their own idea of the significance of the various contributions, but we believe that the scientific community is issuing a clear three-part message to public decision-makers, European and international institutions, economic and civil society organisations and, more broadly speaking, public opinion and all citizens.

**The first message** is that science has established beyond all doubt that climate change is a fact and that Mediterranean societies and ecosystems are some of the most susceptible to these developments.

The Mediterranean is a 'miniature' laboratory due to its geological past, its semi-arid environment with a climate intrinsically different from that of temperate zones as a result of its significant inter-seasonal variations and its role in the turbulent history of human societies. Although it represents only 1.5% of the earth's surface, the Mediterranean is a 'test area' that is home to, and indeed tends to exacerbate, almost all the potentially catastrophic issues facing the entire planet; these include natural risks, global warming, changes in the water cycle, changes to soil and vegetation functions, modifications to biological diversity and biodiversity damage, the unequal distribution of resources and the scaling back of political, economic and social relations between north and south, leading to conflict, large-scale migration, land occupation and rapid urbanisation and coastal development. In addition, it is important to remember the central or peripheral effect the Mediterranean area has on its neighbours, for example the role of Mediterranean climate extremes on the various components of the Earth system and the role of hydrological exchanges with the Black Sea and the Atlantic, as water from the Mediterranean flows through the Strait of Gibraltar and affects the European climate.

The Mediterranean is now a major area of investigation for researchers in every scientific field. The modalities and importance of human activity and its ability to reveal completely new perspectives are some of the key themes currently being studied by the scientific community. New approaches to research, which are reviewed in this work, are essential if we are to understand the way in which they operate and develop, whether in terms of systematic approaches to modelling, integration or investigations.

In the current context where, in the absence of radical countermeasures, a global temperature increase of 1.4 to 5.8°C is expected (3 to 7°C for the Mediterranean region by the end of the 21st century), it was the deep waters of the Mediterranean that first registered the greenhouse gas effect and where changes to thermohaline circulation were observed. Scenarios predict that these changes will continue and that there will be a significant reduction in the convection phenomena that lead to the oxygenation of the Basin; this will inevitably affect biogeochemical cycles as well as the ecosystem and its resources. In this region in particular, global changes seem to affect the frequency of extreme events such as cyclogeneses, hydrometeorological or wind phenomena, droughts and soil degradation.

Research must lead to advances in knowledge, so that we can i) improve our understanding of climate change and its features and mechanisms. This will involve studying past climate cycles and the ways in which societies have responded to them, the latest results reported in this book relating to the water cycle, the origin and frequency of extreme events, groundwater (continental, coastal and deepwater) dynamics and seasonal and long-term variability; ii) quantify flows between compartments and their impact on the system, so we can study air quality and active pollutants and understand their impact on human health; iii) characterise the dispersal and intensity of the main practices affecting marine and continental ecosystems. This involves assessing impacts and vulnerabilities in relation to marine resources and ecosystems, with particular focus on the coastal area. The effects on continental ecosystems are more specifically related to terrestrial biodiversity, particularly forests; iv) study the assessment of the Basin, including the direct impact of global warming on health; v) finally, evaluate and manage risks through adaptation, resilience, conservation of resources and prevention.

Although observations and models based on physical, chemical and biological approaches allow researchers to understand and quantify the processes mentioned above, one of the key areas for reflection must focus on the way in which these processes are affected by human activity and the resultant consequences for the evolution of the changing ecosystems. By changing the climate and river systems, changing the chemistry of the atmosphere, lands and water and tapping into natural resources, we are in fact changing the functioning and value of the ecosystem itself.

Only with a systematic approach can we document the current 'crisis' caused by human activity and particularly noticeable in the Mediterranean, and answer questions on the risks related to usages, practices and social views. These risks are linked to i) the geodynamic (seismic, volcanic and gravitational) context; ii) climate (droughts, fires, coastal erosion, changes to marine dynamics and biogeochemical cycles); iii) industrialisation, urbanisation and transport (pollution of air, water, soil and living resources); iv) usages and practices relating to the quantity and quality of mineral and living resources, biodiversity (land, aquatic and marine), its functions and its services.

This approach to the functioning and functions of the coupled system requires infrastructures and methods for observing and analysing environments and peoples and local strategies adapted to the long term and the short term as well as to the significant seasonal variations found in the Mediterranean. Models and scenarios exist, but need to be improved and regionalised, and other integrated digital tools must be developed. This book is a contribution, albeit a modest one, to the work bravely launched by our Moroccan colleagues so that COP 22 could be an opportunity to support research and the strengthening of the technological and scientific capacities at the heart of climate negotiations. The scientific community is hoping that one of the consequences of this work could be the creation of an inter-country, inter-ministerial and inter-regional authority operational working group to begin the important, in terms of both knowledge and action, work of creating a coordinated observation and surveillance system for Mediterranean anthropo-ecosystems.

The contributions included in this book directly and candidly stress the many remaining uncertainties regarding the real dynamics of the impact of climate change, both in general and across the different spatial scales of the Mediterranean basin.

The **second message** of this work, however, is that these uncertainties must not be used as an excuse for inaction. On the contrary, they must encourage us to better understand the complex causal chains that link climate and the other environmental and anthropic parameters, and to take immediate action to minimise those effects of global change that are threatening the environment and human health and well-being. Some of the contributions show that research provides direct scientific bases for improved management of environments, resources and heritage, for the preservation and strengthening of biodiversity and ecosystem services and for spreading concepts and relevant knowledge throughout society so they reach both decision-makers and the parties involved. In so doing, science is not content to merely report on the risks; it also proposes innovative solutions that could allow us to overcome the barriers currently restricting climate change mitigation and make them easier to adapt, by considering the specific environmental and societal context of a region such as the Mediterranean.

The **third message** is that science is best placed to link the fight against climate change, sustainable development goals and development funding, in accordance with the desire expressed by Christiana Figueres, the previous Executive Secretary of the United Nations Framework *Convention* on Climate *Change*

(UNFCCC), who stated that '*the solutions to climate change offer a portfolio of no-regret policies and actions that are essential for achieving sustainable development*'.

The redefinition of the international agenda in 2015 imposed on us a duty to do so. Prior to COP 21 in December 2015, the 3rd international conference on financing development took place in Addis Ababa in July, followed by the United Nations Summit in New York in September which saw the adoption of the 17 new Sustainable Development Goals (SDG); these are universal goals that, according to the summary report by Secretary General Ban Ki Moon, will create a road to '*dignity for all by 2030*', by '*ending poverty, transforming all lives and protecting the planet*'. As is the case with all international agreements, both the SDGs and the content of the Paris Agreement on climate change, whose initial operational measures are due to be consolidated at COP 22, represented progress we can be proud of, despite the fact that they were inevitably the result of a compromise between different and even contradictory interests and between governments with a large number of downright divergent geostrategic visions and constraints.

The wording of the SDGs reveals inconsistencies that could, if care is not taken, be exacerbated by their implementation; a short-term vision of the requirements for combating poverty or achieving food safety (SDG1 and 2) may, for example, result in technological and economic choices that in the medium term jeopardise the achievement of SDGs 15, 14 and 13 on the preservation of life on land, life below water and combating the effects of global warming respectively. Likewise, meeting the energy needs of developing countries on the southern shore of the Mediterranean and on the African continent in the short term may come into conflict with the need to reduce the carbon intensity of economies in order to combat global warming. And there are many similar examples. Scientific progress can reasonably be expected to produce solutions for reconciling sustainable development goals, creating innovative multi-party coalitions that will be able to impose these solutions in practice and providing enough of the global public goods that the planet needs and of which climate security is one of the best examples.

It has been shown that mankind is finding it very difficult to obtain these public resources to meet the global challenges that, by their very essence, transcend national borders, because it comes up against what political science researchers call the 'Westphalian paradigm', from the name of the 1648 European treaty that for the first time created an international order based on the strict respecting of State sovereignty. Thousands of years of history and the current situation in the Mediterranean have provided many examples of this paradigm. Let's hope that work to combat global warming, in which Morocco and France consider themselves to play a leading role, will help to make the Mediterranean an example of how to move beyond this paradigm and demonstrate solidarity between stakeholders, governments and populations facing joint threats and helping to promote development for the good of all mankind.

# Introduction

## Le changement climatique en Méditerranée

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Le Groupe intergouvernemental sur l'évolution du climat (GIEC), dont les travaux ont joué un rôle-clé dans l'accord « historique » obtenu à Paris, en décembre 2015, lors la 21e Conférence des Parties de la Convention cadre des Nations unies sur les changements climatiques (COP 21), a démontré que le bassin méditerranéen est une des zones de notre planète les plus exposées au changement climatique. En amont de la COP 22, qui se tient du 7 au 18 novembre 2016 à Marrakech, le Maroc a bien voulu accueillir, les 18 et 19 juillet à Tanger, la MEDCOP CLIMAT, le forum méditerranéen pour le climat de tous les acteurs gouvernementaux et non étatiques, qui s'est inscrit dans la continuité de travaux initiés l'année précédente lors de la MEDCOP 21 de Marseille. Dans son message d'introduction à cette MEDCOP 22, Son Altesse Royale Mohamed VI, roi du Maroc, a notamment insisté sur le devoir d'exemplarité de la Méditerranée, dans la construction d'un nouveau mode de consommation et de production et dans l'innovation en matière de lutte contre le changement climatique.

Répondant à une sollicitation des autorités marocaines, notamment de madame Hakima El Haité, ministre chargée de l'Environnement, les 28 organismes membres de l'Alliance pour l'environnement (ALLENVI) publient, à l'occasion de la COP 22, un ouvrage de synthèse exceptionnel. Ce livre s'efforce en effet de présenter un état des lieux de la recherche scientifique de haut niveau sur l'évolution du climat, les conséquences de son dérèglement et les solutions d'atténuation et d'adaptation dans le contexte particulier de la Méditerranée. Il témoigne de la remarquable mobilisation des scientifiques, chercheurs et universitaires, des deux rives de la Méditerranée, pour comprendre les mécanismes du changement climatique sur l'actuel comme sur la longue durée ; les impacts du dérèglement climatique sur l'environnement, l'économie, la santé, les sociétés ; mais aussi pour suggérer et recommander des réponses, fondées sur l'« évidence scientifique » avec les adaptations, les résiliences, la conservation des ressources ou la prévention des risques. Cet ouvrage rassemble une large communauté scientifique, qui s'est mobilisée depuis plusieurs années afin de rendre compte de toute la complexité de l'objet Méditerranée, de créer les conditions d'une meilleure connaissance réciproque au croisement de questionnements scientifiques à définir étape par étape, dans une perspective de décloisonnement disciplinaire.

Riche par la diversité et la qualité des contributions, cet ouvrage ne prétend pas à l'exhaustivité. Certaines thématiques clés comme, par exemple, la place de la réduction des émissions de gaz à effet de serre ou des innovations énergétiques dans les processus d'atténuation, ne sont qu'effleurées. Par ailleurs, certains chapitres mettent en exergue les limites des résultats acquis (à titre d'exemple, la limitation des observations et des simulations climatiques dans l'étude des événements hydrologiques extrêmes, ou encore le manque de données sur le long terme sur les impacts du changement climatique sur la santé humaine), révélant des pans de recherche en devenir ou encore à construire.

Le lecteur pourra se faire sa propre idée de la portée des différentes contributions contenues dans cet ouvrage, mais il nous semble, qu'à travers ce livre, la communauté scientifique envoie un triple et fort message aux décideurs publics, aux institutions européennes et internationales, aux acteurs économiques et de la société civile, et plus largement aux opinions publiques et à l'ensemble des citoyens.

**Le premier message** est que la science a établi, sans contestation possible, la réalité du changement climatique et le fait que les écosystèmes et les sociétés méditerranéennes sont parmi les plus menacées de la planète par cette évolution annoncée du climat.

De par son passé géologique, de par son environnement semi-aride dont le climat se distingue intrinsèquement des zones tempérées par ses fortes variations inter-saisonnières, comme de par son rôle dans l'histoire tourmentée des sociétés humaines, la Méditerranée constitue un laboratoire « en miniature ». Quoiqu'elle ne représente que 1,5 % de la surface terrestre, la Méditerranée constitue une « zone test » qui concentre la quasi-totalité des enjeux potentiellement catastrophiques pour la planète entière et qui tend à les exacerber : risques naturels, réchauffement climatique, modification du cycle de l'eau, changements des fonctions des sols et des couvertures végétales, modifications de la diversité biologique et atteintes à la biodiversité, répartition inégale des ressources, contraction des rapports politiques, économiques et sociaux Nord-Sud débouchant sur des conflits, flux migratoires massifs, occupation des territoires, urbanisation et littoralisation rapides. De plus, centrale ou périphérique, on ne saurait oublier l'impact de la zone méditerranéenne sur les régions avoisinantes : rôle des extrêmes climatiques méditerranéens sur les diverses composantes du système Terre, rôle des échanges hydrologiques avec la Mer Noire et avec l'Atlantique, les eaux méditerranéennes transitant par le détroit de Gibraltar influençant le climat européen.

La Méditerranée est, dès lors, un champ d'investigation consolidé pour de nombreux chercheurs dans tous les domaines scientifiques. Les modalités, l'importance de l'anthropisation et sa capacité à faire apparaître des contextes totalement originaux constituent des éléments centraux de la réflexion scientifique. De nouvelles approches de recherche, dont cet ouvrage rend compte de l'état actuel d'avancement, sont nécessaires pour en comprendre les modalités de fonctionnement et d'évolution, qu'il s'agisse des approches de modélisation, d'intégration ou d'investigations systémiques.

Aujourd'hui où une augmentation de la température mondiale de 1,4 à 5,8 °C est, en l'absence de contre-mesures radicales, attendue (3 à 7 °C pour la région méditerranéenne à la fin du XXIe siècle), ce sont les eaux profondes de la Méditerranée qui, en premier, ont enregistré l'effet de serre ; les observations notent des modifications de la circulation thermohaline ; les scenarii prévoient la poursuite de ces changements et une forte atténuation des phénomènes de convection à l'origine de l'oxygénation du bassin, ce qui n'est pas sans conséquence sur les cycles bio-géo-chimiques, l'écosystème et ses ressources. Particulièrement dans cette région, les changements planétaires semblent affecter la fréquence d'occurrence des événements extrêmes : cyclogenèses, phénomènes hydrométéorologiques ou éoliens, sécheresses et dégradation des sols.

L'avancée des connaissances, alimentée par la recherche, est indispensable afin : i) de connaître les changements climatiques, leur dynamique et leurs mécanismes. Cela se fait au travers de la connaissance des cycles climatiques passés et les réponses des sociétés humaines, les derniers résultats évoqués dans cet ouvrage concernant le cycle de l'eau, l'origine et la fréquence des événements extrêmes, la dynamique des eaux (continentales, côtières et profondes) et sa variabilité saisonnière et à long terme ; ii) de quantifier les flux d'échanges entre les compartiments et leur impact sur le système, d'évaluer la qualité de l'air et les polluants actifs et de comprendre leur impact sur la santé des populations ; iii) de caractériser la dispersion et l'intensité des principaux usages impactant les écosystèmes marins et continentaux. Il s'agit d'établir le bilan des impacts et des vulnérabilités sur les ressources marines et les écosystèmes marins, une attention particulière devant être apportée à la zone côtière. Les impacts sur les écosystèmes continentaux concernent quant à eux plus particulièrement la biodiversité terrestre, et notamment les forêts. iv) de réaliser le bilan sanitaire du bassin, avec l'impact direct du réchauffement climatique sur la santé ; v) enfin, l'évaluation et la gestion des risques au travers de l'adaptation, la résilience, la conservation des ressources et la prévention.

Si les observations et modèles fondés sur des approches physiques, chimiques et biologiques permettent d'appréhender et de quantifier les processus évoqués ci-dessus, un des éléments centraux de la réflexion doit porter sur la façon dont ils sont modifiés par l'impact des activités humaines et les conséquences qui en découlent pour l'évolution des écosystèmes. En modifiant le climat et le régime des fleuves, en modifiant la chimie de l'atmosphère, des terres et de l'eau, en tirant profit des ressources naturelles, c'est le fonctionnement même et la valeur de l'écosystème qui sont modifiés.

Seule une approche systémique peut permettre de documenter au mieux la « crise » actuelle qui résulte de l'anthropisation, particulièrement sensible en Méditerranée, et de répondre aux questions sur les risques, considérés en rapport avec les usages, les pratiques et les représentations sociales : i) risques liés au contexte géodynamique (sismiques, volcaniques, gravitaires) ; ii) risques liés au contexte climatique (sécheresses, feux, érosion du littoral, modifications de la dynamique marine et des cycles biogéochimiques) ; iii) risques liés à l'industrialisation, à l'urbanisation et aux transports (pollution de l'air, de l'eau, des sols et des ressources vivantes) ; iv) risques liés aux usages et pratiques sur la quantité et la qualité des ressources minérales et vivantes, sur la biodiversité (terrestre, aquatique et marine), ses fonctions et ses services.

Cette approche du fonctionnement et des fonctions du système couplé exige des infrastructures et des moyens d'observation et d'analyse des milieux et des populations, des stratégies de terrain adaptées au long terme, au court terme et à la saisonnalité particulièrement marquée en Méditerranée. Modèles et scenarii existent mais doivent être améliorés, régionalisés, et d'autres outils numériques fédérateurs doivent être développés. Cet ouvrage constitue d'ailleurs une contribution, certes modeste, à l'action courageusement initiée par ailleurs par nos collègues marocains pour faire de la COP 22 une occasion de mettre le soutien à la recherche et au renforcement des capacités technologique et scientifique au cœur de la négociation climatique. L'une des retombées de ces efforts, que la communauté scientifique appelle de ses vœux, pourrait être de constituer un groupe de travail opérationnel, inter-pays, inter-ministériel et inter-collectivités territoriales, pour s'atteler au chantier décisif, tant pour la connaissance que pour l'action, de construction d'un dispositif coordonné d'observation et de surveillance des anthropo-écosystèmes méditerranéens.

Les contributions incluses dans ce livre ne manquent d'ailleurs pas de souligner, avec rigueur et honnêteté, les fortes incertitudes qui persistent quant à la dynamique réelle de l'impact du changement climatique, en général et aux différentes échelles spatiales du bassin méditerranéen.

Cependant, **le deuxième message** de cet ouvrage est que ces incertitudes ne doivent pas servir de prétexte à l'inaction. Au contraire, elles doivent nous inciter à mieux comprendre les chaînes causales complexes qui relient le climat et les autres paramètres environnementaux et anthropiques, et à agir sans tarder afin de minimiser celles des conséquences du changement global qui menacent l'environnement, la santé et le bien-être des populations. Plusieurs des contributions démontrent que la recherche fournit directement des bases scientifiques pour une meilleure gestion des milieux, des ressources et des patrimoines, pour préserver et renforcer les services de la biodiversité et des écosystèmes, et pour diffuser les concepts et les connaissances appropriées dans la société, chez les décideurs comme chez les acteurs concernés. Ce faisant, la science ne se contente pas de faire le constat des risques qui nous menacent mais propose des solutions innovantes qui peuvent permettre de dépasser les blocages qui freinent actuellement l'atténuation du changement climatique et qui facilitent l'adaptation en tenant compte des spécificités du contexte environnemental et sociétal d'une région comme la Méditerranée.

Le **troisième message** est justement que la science est l'outil le mieux à même de lier la lutte contre le changement climatique, les objectifs du développement durable et le financement du développement, conformément au souhait exprimé par Christiana Figueres, la précédente secrétaire exécutive de la *Convention* cadre des Nations unies sur le changement *climatique* (CNUCCC), que « les solutions au changement climatique procurent un éventail de politiques et de mesures sécurisées qui sont essentielles pour atteindre un développement durable ».

La redéfinition de l'agenda international qui est intervenue au cours de l'année 2015 nous en fait d'ailleurs une obligation puisqu'avant la COP 21 de décembre 2015, s'étaient successivement tenues, en juillet à Addis-Abeba, la 3e Conférence internationale sur le financement du développement et, en septembre à New-York, le sommet des Nations unies qui a vu l'adoption des 17 nouveaux Objectifs du développement durable (ODD), objectifs universels censés, selon le rapport de synthèse du secrétaire général Ban Ki Moon tracer la route vers « la dignité pour tous d'ici à 2030 » en « éliminant la pauvreté, en transformant nos vies et en protégeant la planète ». Comme tout consensus international, tant les ODD que le contenu de l'accord de Paris sur la lutte contre le réchauffement climatique, dont la COP 22 s'efforcera de concrétiser les premières traductions opérationnelles, ont représenté des avancées dont on peut se féliciter mais ont inévitablement été le fruit d'un compromis entre intérêts différents, voire contradictoires, et entre des gouvernements dont les contraintes et visions géostratégiques sont multiples, voire franchement divergentes.

Les ODD dans leur lettre même ne sont pas exempts d'incohérences que leur mise en œuvre effective peut, si l'on n'y prend pas garde, exacerber : une vision à court terme des nécessités de la lutte contre la pauvreté ou pour la sécurité alimentaire (ODD 1et 2) peut, par exemple, favoriser des choix technologiques et économiques qui hypothèquent à moyen terme la réalisation des ODD 15, 14 et 13 qui concernent respectivement la préservation de l'environnement terrestre, des océans et contre les effets du réchauffement climatique. De même, la satisfaction à court terme des besoins énergétiques des pays en développement de la rive sud de la Méditerranée comme du continent africain peut se heurter à la nécessaire décarbonation des économies qu'impose la lutte contre le réchauffement planétaire. Et, on pourrait multiplier les exemples analogues. Ce sont des avancées de la science que l'on peut raisonnablement attendre des solutions qui permettent de concilier les objectifs de développement durable, de construire les coalitions innovantes d'acteurs qui permettront de les imposer en pratique, et de fournir en quantité suffisante les biens publics globaux dont la planète a besoin et dont la sécurité climatique est l'une des illustrations les plus caractéristiques.

Il est avéré que l'humanité éprouve de graves difficultés à se doter de tels biens publics pour faire face à des enjeux globaux qui, par essence, dépassent les frontières nationales car elle se heurte à ce que les chercheurs en science politique qualifient de « paradoxe westphalien », du nom du traité européen de 1648 qui instaura, pour la première fois, un ordre international fondé sur le strict respect de la souveraineté des Etats. L'histoire millénaire, comme l'actualité récente, de la Méditerranée ont maintes fois illustré ce paradoxe. Espérons que la mobilisation contre le réchauffement climatique, dont le Maroc et la France se veulent l'un des fers de lance, contribuera à faire de la Méditerranée l'exemple de son dépassement et de la solidarité entre les acteurs, les gouvernements et les populations face aux périls communs et pour un développement au service de l'Homme.

Part 1

# Mechanisms, observed trends, projections

Chapter 1

# People and climate change in the past

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## Abstract

The current climate change has encouraged interdisciplinary collaboration to better understand the role that climate may have played in the development of past Mediterranean societies. Over the past twenty years, palaeoenvironmental research in the Mediterranean has progressed significantly, mainly based on marine, lake, marsh, peat bog and fluvial archives. These records demonstrate the long anthropogenic impact on the Mediterranean ecosystems but also provide evidence of significant climatic instability with notable periods of rapid climate change (RCC) at the global scale during the Holocene (9.2, 8.2, 6-5, 4.2, 3.2 ka cal. BP (*c.* 7.2, 6.2, 4-3, 2.2, 1.2 ka BC). The study of the climate in the last millennium is of particular interest because this period encompasses the most recent pre-industrial warm interval known as the Medieval Climate Anomaly followed by the coldest centuries of the Little Ice Age, which was interrupted around 1850 by the industrial era. In parallel with major progress in generating proxy signals, model simulations of the climate in last millennium using state-of-the-art coupled ocean-atmosphere models in the Coupled Model Intercomparison Project (CMIP) allow cross-analyses of proxy and model data to explore the physical mechanisms at play and the role of external factors like solar activity, volcanism, land use and greenhouse gases in climate variability.

# Résumé

Le changement climatique observé actuellement stimule l'interdisciplinarité et les collaborations entre scientifiques, l'objectif étant de comprendre, le plus finement possible, le rôle que le climat a joué au cours du passé, dans le développement des sociétés méditerranéennes. Depuis plus de trente ans, les recherches sur les paléo-environnements en régions méditerranéennes ont fortement progressé ; elles se fondent, la plupart du temps, sur les archives du sol, des sédiments marins, des lacs, marais et tourbières et des archives fluviales. Les résultats montrent l'impact des sociétés humaines sur les écosystèmes méditerranéens sur le long terme. Ils apportent aussi la preuve d'instabilités climatiques avec des périodes de changement rapide (RCC) observées à une échelle globale au cours de l'Holocène (9.2, 8.2, 6-5, 4.2, 3.2 ka cal. BP (*c.* 7.2, 6.2, 4-3, 2.2, 1.2 ka BC). L'étude du climat du dernier millénaire est particulièrement intéressante car elle englobe la période de réchauffement pré-industrielle la plus récente, connue sous le nom d'anomalie climatique médiévale, suivie par le petit âge glaciaire qui s'interrompt vers 1850 avec l'ère industrielle.

En parallèle, les progrès des techniques de recherche, la production d'analyses multiproxy et de modèles de simulations permettent, en couplant les modèles océan-athmosphère avec les modèles du projet d'intercomparaison (projet CMIP), des analyses croisées. Ils autorisent la production de modèles, qui explorent le rôle des mécanismes physiques et des facteurs externes comme l'activité solaire, le volcanisme, l'utilisation des terres et les gaz à effet de serre dans la variabilité du climat.


# Introduction

The Mediterranean is one of the regions with the longest and most intense human occupation in the world. Here, human societies have been constantly confronted with a fragile and contrasted environment subject to recurring crises. Interactions between human societies and their environment successively shaped the territory, resulting in recognisable characteristics, but also making it vulnerable, exposed to natural risks and in a precarious balance. Because it has been subjected to a wide range of climates, and political and socio-economic conditions for millennia, the Mediterranean region is a true model of human-environment co-evolution, and can provide a wealth of information on the vulnerabilities of its "anthropo-systems", but also on its capacities of resilience and its ability to take advantage of environmental requirements.

Ongoing processes and the dynamics of the contemporary ecological systems are the result of mechanisms inherited from events that occurred in the past, even the recent past. The longstanding intense human occupation combined with variations in climate led to the degradation of biological and ecological resources. The intense exploitation of these resources has resulted in strong pressures on Mediterranean hydrological and biogeochemical cycles, thereby increasing environmental degradation to an even greater extent.

This is the context in which studies of these processes and their interactions are being conducted at different temporal and spatial scales, in the knowledge that the mechanisms concerned are still not sufficiently well understood to enable the production of reliable models and forecasts. Because of the ecological, social and economic stakes involved, predicting the effects of climate change, land use, natural resources and the evolution of the ecosystems mobilises numerous researchers. The overall aim is to improve the construction of long-term scenarios concerning two main issues: 1) the complexity of scales and of transformations in the relation between human societies and their territory to improve our understanding of the role of agro-systems and their management in shaping the evolution of the human societies, 2) improving management decisions thanks to scientific knowledge and based on the cultural traditions of the populations concerned, both of which are fundamental for the survival of the Mediterranean region.

The historical aspects of the relationships between the societies and the environment they built and shaped over time are central to current thinking on the eco-anthropo-systems and biodiversity in the Mediterranean region.

Understanding natural climate variability and the role of human activities in ongoing changes requires long term pre-instrumental records. Such records are presented in this chapter together with some results of research on rapid climate change and social transformations in the Mediterranean region. Uncertainties, adaptability and resilience are used to inform the quite near future, illustrated with a concrete example of climatic and hydrological changes in the Moroccan Middle Atlas evidence by lake sediment archives.

# Introduction

La Méditerranée constitue l'une des régions au monde les plus intensément occupées par l'homme et cela dans la longue durée. Les sociétés méditerranéennes ont été constamment confrontées à un milieu fragile et contrasté, sujet à des crises récurrentes. L'interaction avec ce milieu a façonné, par couches successives, un territoire aux caractéristiques bien identifiables mais également vulnérable, exposé à des risques naturels et en équilibre précaire. Néanmoins, le bassin méditerranéen, qui a expérimenté une grande richesse de conditions climatiques, politiques et socio-économiques depuis des millénaires, est un modèle de co-évolution homme-milieu riche d'informations sur les vulnérabilités de ses anthroposystèmes, mais aussi sur ses capacités de résilience, et enfin ses capacités de tirer parti des contraintes environnementales.

Le jeu des processus actuels et les dynamiques des systèmes écologiques contemporains répondent à des mécanismes étroitement hérités des événements du passé, même récent. Les écosystèmes méditerranéens subissent une occupation humaine ancienne et prononcée, dont la conséquence, conjuguée aux variations du climat, est une dégradation des ressources biologiques et écologiques. L'intensité de leur exploitation aboutit à des pressions fortes sur les cycles hydrologiques et biogéochimiques accentuant plus encore la dégradation des milieux.

C'est dans ce contexte que les études sur les processus et leurs interactions aux diverses échelles de temps et d'espaces sont menées, sachant que ces mécanismes ne sont pas encore suffisamment connus et compris pour que soient entrepris des modèles et des prévisions fiables. En raison des enjeux écologiques, sociaux et économiques, la prospective dans le domaine des effets des changements climatiques et de l'utilisation des terres sur les ressources naturelles et l'évolution des écosystèmes mobilise une grande partie des chercheurs. Il s'agit d'évaluer la recherche pour améliorer le processus de construction de scénarios à long terme, autour de deux questions : la notion de complexité d'échelles et de transformations dans la relation société-territoire pour améliorer la compréhension du rôle des hydro-agrosystèmes et de leur gestion dans l'évolution des sociétés, la remédiation des modes d'élaboration des décisions de gestion, en fonction des connaissances scientifiques et de la culture des populations, questions fondamentales pour la survie en Méditerranée.

Les aspects historiques des relations entre les sociétés et leur environnement, qu'elles ont construit et façonné au cours du temps, constituent une thématique centrale de la réflexion sur les éco-anthroposystèmes et la biodiversité en Méditerranée.

Comprendre les changements climatiques et le rôle des activités humaines sur leur évolution demande des données sur la longue durée, présentées dans ce chapitre, tout comme sont exposés les résultats sur les changements rapides et les transformations des sociétés dans la région méditerranéenne. L'adaptabilité et la résilience sont évoquées pour éclairer le futur proche. Ces changements sont illustrés par des exemples qui portent sur l'évolution climatique et hydrologique dans le moyen Atlas marocain décrite à partir de l'étude d'archives sédimentaires lacustres.

# Rapid climatic change and social transformations

## Uncertainties, adaptability and resilience

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## Introduction

Over the past twenty years, palaeoenvironmental research in the Mediterranean has progressed significantly, based mainly on marine, lake, marsh, peat bog and fluvial archives. These records demonstrate a long-standing anthropogenic impact on the Mediterranean ecosystems but also provide evidence of significant climatic instability (e.g. Magny et al. 2013; Vannière et al. 2013) with notable periods of Rapid Climatic Change (RCC) observed on the global scale during the Holocene (9.2, 8.2, 6-5, 4.2, 3.2 ka cal. BP; *c.* 7.2, 6.2, 4-3, 2.2, 1.2 ka BC). In polar records, RCCs that start abruptly within a decade or two at the most and most often concern a period of 150 to 400 years, are often considered among the main environmental factors causing socio-economic and cultural changes, migrations, and even collapses.

According to such climatic determinism, an RCC would be much harder (if not impossible), for a human society to adapt to, thus leading to radical societal transformations (e.g. Weiss et al. 1993; DeMenocal, 2001; Drake, 2012; Weninger et al. 2014) but an increasing number of published studies suggest that the relationship between environmental and cultural changes is more complex and offer a range of non-deterministic explanations (e.g. Butzer, 2012). Starting from this perspective, we have developed a new research project (ArcheoMed-Paleomex) in the framework of the MISTRAls initiative to respond to the following questions:

1) What is a natural forcing (timing, nature, origin)?

2) How can a so-called "climate event" produce a social fact: change in material production, resource exploitation, settlement pattern, etc.?



## Methods

We have conducted new archaeological and palaeoenvironmental investigations on an intermediate scale, enabling the cross-comparison of social and environmental data (e.g. Carozza et al. 2012, 2016; Ghilardi et al. 2012, 2016; Glais et al. 2016) to move beyond the observation of co-occurrence and the hypothetical causal link between climate and social change.

Like Flohr et al. (2015) in a recent synthesis about the human consequences of 8.2 and 9.2 ka events in the Near East and in the eastern Mediterranean area, we believe that "more site-specific detailed studies focusing on one ecological base and strategies are needed" and that "this 'bottom-up' approach is now the best way to further the debate. […] This approach will be time consuming but very worthwhile".

We have developed a multi-scalar approach from the local site (continental natural archive near archaeological sites) to the regional scale. It will then be possible to develop more general conclusions on interactions between nature and society from the local scale to the regional scale – which is also that of the cultural areas – to the entire Mediterranean area. In practical terms, we have developed research in various areas from the south-western to the northeastern part of the Mediterranean basin.

Three main transects are organized in different investigation windows (fig. 1):

(1) The 'Go-West' transect goes from Eastern Anatolia to the Adriatic, passing through Central Anatolia, Western Anatolia, the western Black Sea coast and Danube delta, Cyprus, Crete, Northern Greece and Corfu Island;

(2) The "Gulf of Lion-Southern Alps" transect comprises the Southeastern French Alps, the Côte d'Azur, Languedocian Lagunas, a small continental depression in French Languedoc and Roussillon, Corsica Island and the Balearic islands;

(3) The "Maghreb" transect comprises 3 working areas: the Middle Atlas and the Moulouya River basin in Morocco, the Oued Cheliff river basin in Algeria, the Medjerda and Oued Zeroud-Merguellil river basins in Tunisia.

In each window, we develop multi-proxy palaeoenvironmental analyses (geomorphology, sedimentology, geochemistry, micromorphology, palynology, non-pollen palynomorphs, fire signature, phytoliths, etc.) around archaeological sites and geoarchaeological research into excavated sites, where archaeobotanical and archaeozoological research were also conducted. To present our investigations, we briefly summarize results the obtained on the regional scale in 4 RCC periods from the Early Holocene and the Neolithization process to the Late Holocene.

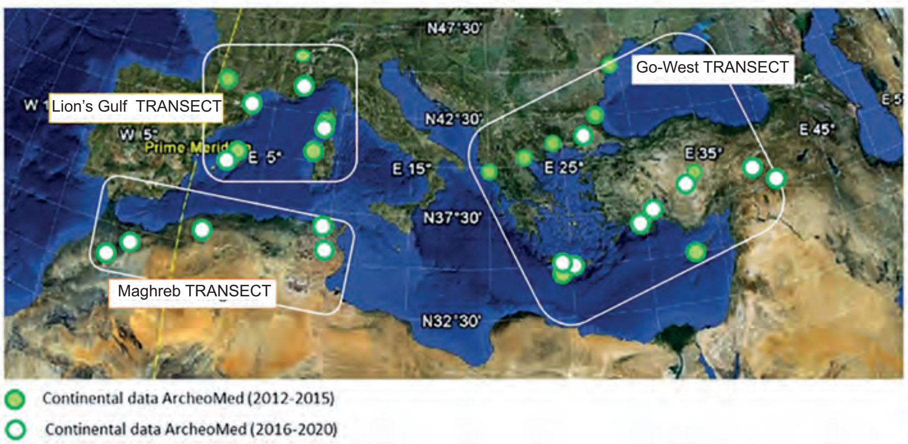


*Figure 1*
*Areas investigated by the ArcheoMed-Paleomex project.*

## 8.2. ka BP event and the Neolithization of Eastern Mediterranean

The first question concerns the Early Holocene RCC's records in the Mediterranean zone, which are under-represented in continental archives (9.2 and 8.2 ka events, c. 7.2 and 6.2 ka BC) and their impact on prehistoric societies.

We study river and lake systems, from the eastern to the central Mediterranean areas (Central Anatolia, Cyprus, NE and NW Greece) which represent continental archives where Early Holocene RCC events and their local impact on prehistoric societies can be or have been recorded.

The research demonstrates the reality of hydrogeomorphological responses to early Holocene RCCs in valleys and alluvial fans and lake-marsh systems (Berger et al. 2016). It highlights the importance of Holocene sedimentation and post-depositional disturbances on reading the Mesolithic-Early Neolithic transition and attests to the first true levels of Neolithic occupation in SE Europe. Terrestrial records still reflect heterogeneities in palaeoclimatic restitution across the north-eastern Mediterranean during RCC events. They suggest a probable tripartite timing for the 8.2 ka BP event revealed by a few Mediterranean marine records. These issues are crucial if we are to reach a clearer assessment of climate impact on coastal and continental environments, in major societal disruptions such as the Neolithization of the Mediterranean.

The probable tripartite timing of the 8.2 ka events complicates our view of the link between climate change and the Neolithic development and colonization of Europe. Our hypothesis of an early Neolithic colonization of the North Aegean (around 8.4 ka cal. BP), prior to the assertion of the second and more marked part of the 8.2 RCC event well registered in the western study area demonstrates the complexity and the reality of the climate change but also questions its link with the Neolithization promoted by certain researchers (e.g. Wenninger et al. 2014). We must keep in mind that the geographical setting of the Mediterranean results in physically very contrasting environments in which it is often sufficient to move over very short distances to find different environmental conditions (Lespez et al. 2016b). In fact, a dry period could imply a move closer to water resources or, on the contrary, as observed in Dikili Tash, a rise of water table and flood hazards might imply leaving the floodplain to settle higher on the alluvial fans or lower slopes in the surrounding areas. Only new research, closely interlinked with the multidisciplinary analyses of intra-archaeological sites will optimize our perception of forms of socioenvironmental resilience.



## 6.5-5 ka BP Rapid Climatic Changes and the "lost millennium" in SE Balkan archaeology

The second results discuss the interaction of nature and society in the Middle Holocene. At the end of the Late Neolithic, the period between 6.5 and 5 ka cal BP (c. 4.5-3 ka BC) is one of the least studied episodes of RCC. This period is characterized by a dramatic decline in settlement and a cultural break lasting over 5 centuries in the South Balkans (Tsirtsoni, 2016). High-resolution paleoenvironmental proxy data obtained in northern Greece enables an examination of the societal responses to rapid climatic change (Lespez et al. 2016). The development of a lasting fluvio-lacustrine environment followed by enhanced fluvial activity is evident from 6 ka cal BP (c. 4 ka BC) in the Lower Angitis and Strymon valley. Palaeoecological data show a succession of three dry events at 5800–5700, 5450 and 5000–4900 cal yr BP.

By comparison with the available regional data, it appears that these events correspond to the incursion of cold air masses to the eastern Mediterranean, confirming the climatic instability of the middle Holocene climate transition. Two periods with farming and pastoral activities during the Late to Final Neolithic (6.3–5.6 ka cal BP, c. 4.3-3.6 ka BC) and the Early Bronze Age (5.1–4.7 cal BP, c. 3.1-2.7 ka BC) evidently correspond to an increase in settlements on the regional scale. The intervening period is marked by environmental changes, but the continuous occurrence of anthropogenic taxa and fire signatures suggests the persistence of human activities and in particular, pastoralism, despite the lack of archaeological sites dated to this period and the weakness of archaeological evidence of continuity, raising the question of changes in settlement patterns.

The populations moved to cope with environmental change, but although they moved away from areas most affected by the rising water table, they probably settled in the foothills. The permanence, even slightly diminished, of anthropogenic indicators confirms the continuity of settlement in the Lower Angitis and Strymon Valley. As in other Eastern Mediterranean areas (e.g. Ghilardi et al. 2015), the abrupt succession of wet and dry periods could have affected the population of Northern Greece, but it is likely that the dry and cool conditions of the short-time climate events alone were insufficient to trigger the observed societal changes. Archaeological surveys must be developed at the micro-regional scale in order to better understand the changes in the settlement patterns. This study highlights the high capacity for adaptation of Neolithic and Bronze age societies during climatic stress periods.

## 4.2 ka BP climatic event and settlement pattern changes in western Mediterranean

The third study focuses on the impact of environmental changes (so-called 4.2 ka BP event, c. 2.2 ka BC) on ancient societies, from the recent Neolithic to the Early Bronze Age in western Mediterranean areas (Carozza et al. 2015). A short period of drought in the Mediterranean may correspond to the establishment of the Mediterranean climate under orbital forcing (Magny et al. 2013).

A series of studies have established that in the south of France, for instance in the Rhône valley, an important change occurred in the human settlement system around 2.3-2.2 ka BC. In lowland areas, after maximal concentration, the number of settlements decreased significantly along the river systems during a period of very high hydrosedimentary discharges, dryness, and fire activity (fig. 2). It is interesting to note that the exploitation of copper ore resources, which had begun in Cabrières (SW France) around 3.2 ka BC ceased around 2.3–2.2 ka BC.

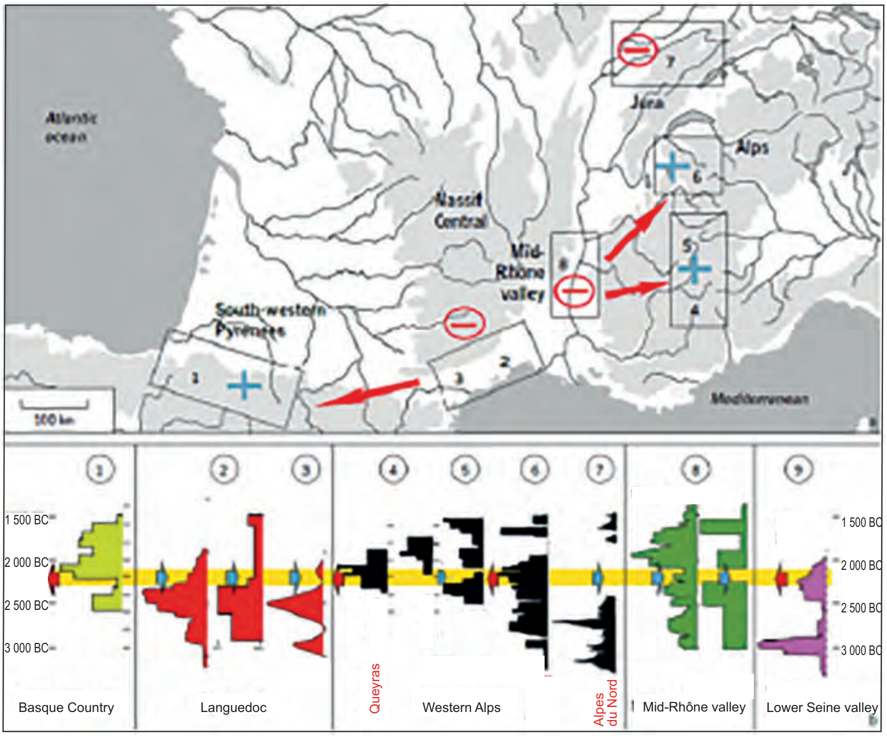


*Figure 2*
*Map of the micro-regions documenting the Late Neolithic III to Early Bronze Age transition around 4.2 ka cal BP (c. 2.2 ka BC).*
*1 Western Pyrenees; 2 Languedoc plateau (Boussargues-Les Vautes); 3 Languedoc (Fontbouisse Culture); 4 southern Alps (Queyras, Saint-Véran); 5 central-western Alps (CPDF); 6 northern Alps (multi-source CPDF); 7 Jura/Swiss Plateau/Bavaria; 8 mid-Rhône valley; 9 Normandy (Alizay site, CPDF). Red minus signs – depopulated areas; blue plus signs – densely populated area; red arrows – direction of possible mobility of people around the 4.2 ka cal BP event. b Comparison of temporal dynamics of the same micro-regions illustrating spatial re-organisation throughout France. Blue arrows – sharp decline; red arrows – growth.*
*From Carozza et al. 2015.*

At the same time, environmental changes allowed for an exploitation of alpine copper, as seen in Saint-Véran (SE France). Indeed, from 2.15–1.65 ka BC, the glacial retreat permitted the exploitation of copper ore resources at very high altitudes of above 2,400 m (Les Rousses, SE France). The archaeological findings have revealed a growth in human pressure in mountain areas, specifically in the Pyrenees (SW France). The exploitation of intermediate areas (from foothills to moderately mountainous regions) in the Basque Country took the form of temporary habitations (pastoralism). The period between 2.3 and 2.1 ka BC corresponds to a global environmental threshold phase in the south-north atmospheric circulation at the beginning of the Late Holocene, caused by an orbital forcing. In the same period, the effects of millennial-scale Rapid Climate Change (RCC) lasting three to four centuries (around the 4.2 ka BP event, c. 2.2 ka BC) are recorded in the lake, fluvial and soil systems of Western Europe. It still seems to present a temporal tripartite structure with two wet periods in Southern France (Magny et al. 2013, Carozza et al. 2015). The socio-economic modifications show a decrease in lowland area occupation and an increase of settlement in mountainous areas and may have resulted in a spatial reorganization at a regional level, but not in a global societal collapse.

## 3.2 ka BP climatic event and sustainability of agro-pastoral activities in Eastern Mediterranean

The last case study concerns the transition from the Iron Age to the Middle Ages in the eastern Mediterranean area. In Anatolia, a complex rural system has been identified in many pollen records (Bottema and Woldring, 1984): the "Beyşehir Occupation Phase" (BOP). It is characterized by complementary productions (fruits, cereals, trees, vineyards, olives, animals etc.) and its chronology varies from place to place (Kuzucuoğlu, 2015; fig. 3). Depending on the recording site, it appears during the Late Bronze Age (LBA, the Hittite Empire), during the chiefdom and rural transition between LBA and Iron Age kingdoms (1.15-1 ka BC), and the beginning of the Iron Age (1-0.7 ka BC). It lasted until the Early Byzantium, ending at places between AD 450 and 750 (1.5-1.2 ka BP). While the end of the BOP is well correlated in central Anatolia with the Arab raids, its end in other areas seems to be more or less related to a contraction in rural settlement with no clear cause, mainly because it varies so significantly from region to region. The exceptional duration (> 1,000 years) of the BOP landscape in Anatolia, occurred in spite of many, well known, political turmoil and wars, as well as several, well known, climatic changes that succeeded in the Eastern Mediterranean from ca 1.3 ka BC to 0.7 ka AD. The example of the "3.2 ka cal. BP event", well identified in central Anatolia (Kuzucuoğlu, 2015), is a good illustration of the necessary caution and nuancing required when arguing a decisive role for climate in the fate of major political events such as the silent vanishing of the Hittite Empire c. 1.17 ka BC (without destruction). Central Anatolia is a region sensitive to rain-depletion-climatic "crises". In spite of the limits in $^{14}C$ dating inducing a c. 50-year leeway in the start and end dates of "rapid changes", climatic fluctuations as well as abrupt changes can be evidenced in several areas forming the large central Anatolian region, even when wet/dry alternations have been rapid.

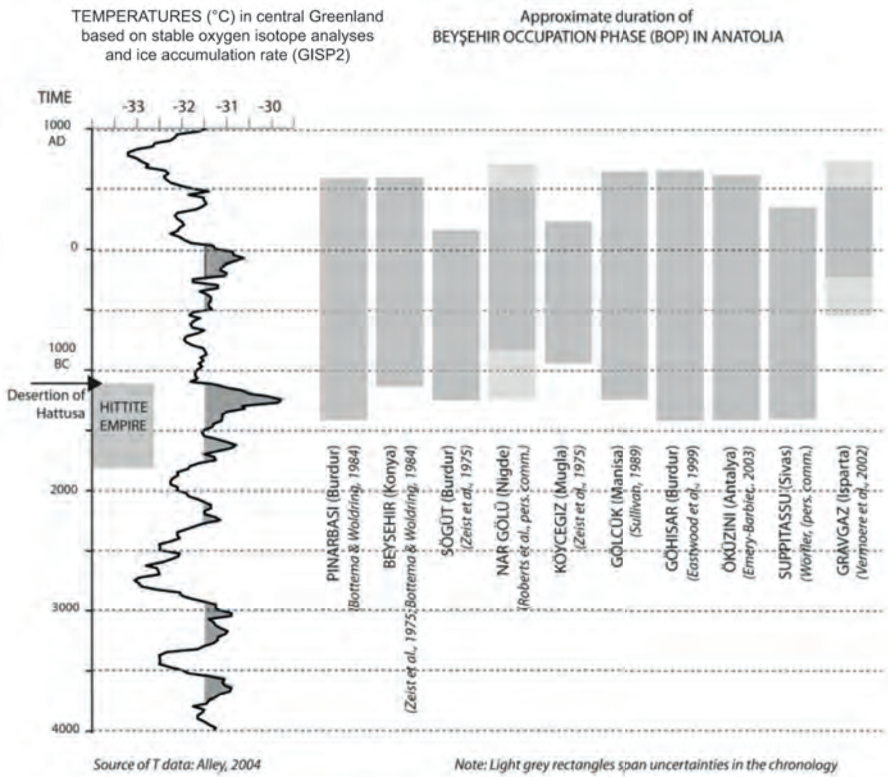


*Figure 3*
*Climatic changes from the Hittite Empire to the medieval period and BOP timing in Anatolia. From Kuzucuoglu, 2015.*

Here, the 2nd half of the 2nd mill. BC (1.55-1 ka BC, 3.5-3 ka cal. BP) and the start of the 1st mill. BC (1-0.85 ka BC, 3-2.8 ka cal. BP) were characterized by several dry periods and drought spikes recorded by indicators in marsh, lake, river and slope sediments. Here several facts contradict the deterministic view of the climate role in history which assumes that climate causes both an irreversible decline of agriculture during increasing periods of dryness, and political destabilization resulting from migrations and wars motivated by resource depletion.

In fact, at the end of the 2nd mill. BC, neither the droughts nor the vanishing of the Hittite Empire, impacted the BOP at sites where it had started before 1.2 ka BC. During the so-called "3.2 ka cal. BP global event", the BOP proved its sustainability in spite of political changes and continuing dry conditions. The climate degradation which occurred in parallel with cultural disorders in the Eastern Mediterranean (Kuzucuoğlu 2012), acted in Anatolia as an external element leading, in the context of the disruption of the EM "world trade organization", to the end of a very centralized system and the development of an innovative cultural system. This example shows also that the degree of cultural sensibility to climate change is not obviously related to the intensity or nature of that change, but to the internal factors of vulnerability with regard to change: rigidity of social structures, centralization of decision, transmission networks, unbalanced distribution of resources and means for productions (e.g. equipment, land, technical innovation).



## Conclusion

These 4 examples underline the uncertainties of chronology of so-called RRC at the local/regional scale without specific investigations and highlight the capability of societies to be resilient and/or to adapt to environmental transformations caused by climatic changes. Rather than collecting radiocarbon dates in order to propose the modelling of Nature/Society interactions, we need to have more case studies on a regional and Mediterranean scale if we are to reasonably discuss the role of climatic changes in cultural transformation. Where archaeological and local palaeoenvironmental data are still unexploited, our understanding of land use and historical dynamics is hindered, with many surprises still in store.

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# Improving knowledge on the climate and environmental context of past Mediterranean societies

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## Introduction

The Holocene, our present interglacial, has long been considered as a stable climate period. However, paleoclimate reconstructions produced in recent decades have shown that the Holocene climate has been variable at millennial to centennial time scales. Several centennial scale relapses of sustained cold and/or dry climate conditions have been documented superimposed on the long-term cooling observed in the extra-tropics since the beginning of the Holocene (Wanner et al. 2011). Some of these abrupt cold climate regimes would have been synchronous with societal collapses, such as that of Akkadian cultures (Weiss and Bradley, 2001). With the recent rise in global temperatures, more rapid and intense events including floods, droughts or heat waves have been observed and are likely to be more frequent with climate change and to have more severe societal impacts.

Understanding natural climate variability and the role of human activities in current climate change requires long pre-instrumental records. Indeed, direct observations of climate variables (i.e. temperature, precipitation) are usually limited to the last hundred years, which is too short to put the observed variability into perspective to see how it compares with the range of pre-industrial variability. The shortness of instrumental records also limits our understanding of low frequency climate variability as well as of gradual trends or sustained periods of floods, droughts and storms. Reconstructions of the pre-industrial climate rely on indirect information based on climate sensitive bio-indicators and geochemical tracers, called *proxies*. The improvement of sampling techniques, the development of new proxies and more robust calibrations has indisputably led to major advances and produced high quality reconstructions of the recent past climate. Proxies have been commonly measured in continental archives such as tree-rings, speleothems or ice cores to estimate past temperatures and precipitation but it is only recently that marine sediments have been explored to produce decadal time scale records of the temperature of the surface ocean, the primary heat reservoir of the Earth (McGregor et al., 2015). Yet accurate dating to assess rates of changes or the synchronicity between records is still problematic. As a complement to sediments, corals yield discontinuous but best dated and seasonally / annually resolved reconstructions thanks to their growth rates that are much larger than sedimentation rates.

The study of the last millennium climate is of particular interest because this period encompasses the most recent pre-industrial warm climate interval known as the Medieval Climate Anomaly followed by the coldest centuries of the Little Ice Age interrupted around 1850 by the industrial era. In parallel with major progress in generating proxy signals, model simulations of the last millennium climate using state-of-the-art coupled ocean-atmosphere models within the Coupled Model Intercomparison Project (CMIP) allow cross-analyses between proxy and model data to explore the physical mechanisms at play and the role of external factors like solar activity, volcanism, land use and greenhouse gases in climate variability. Nevertheless, comparison of proxy data with GCM model simulations is still a critical first step in linking global climate and regional signals with the information collected across site(s) reflecting the impact of climate change on ecosystems and the response of human societies.

# Climate and extreme events in the recent past

The Mediterranean Sea is a unique region to explore the complex interactions between climate, environment and human activity at decadal to millennial timescales (Roberts et al. 2011). Sea level rise and the expected increase in extreme climatic events such as coastal flooding and storm surges are major concerns for populations living in the coastal regions of the Mediterranean. Understanding the frequency of intense storms in the past several centuries to millennia is important to better predict future vulnerability and economic loss. Because extreme events are rare and therefore difficult to observe in a human lifetime, proxy reconstructions are essential to trace their recent history and place them in a longer temporal context.

Within the framework of the international MISTRALS/PaleoMeX program, new approaches have been developed using lagoon sediments distributed across the western Mediterranean Sea (in France, Spain, Morocco, Algeria and Tunisia) to document the recurrence of floods and storms that have stressed the coastline in the past (Figure 1AB). Proxy data have shown that during the Little Ice Age (from ca. 1400 to 1850) storms were more intense and frequent, thus contrasting with the low storm activity in the Medieval Optimum. In lagoons in southern France, stratigraphic data revealed an increase in catastrophic category 3 or more storms during the second half of the Little Ice Age (Dezileau et al. 2011). Longer records covering the past thousand years indicate that enhanced storminess in the western Mediterranean coastal region was coeval with known cold periods in the North Atlantic Ocean and in Europe. During the past 100 years, no major intense storm has directly struck the western Mediterranean area, a situation that has resulted in inadequate policies plus the subsequent construction of buildings and infrastructure (dams, recent harbors) well within the zone of possible storm tide flooding. The population residing on the coast has increased by a factor of 10 since 1700 with a dramatic rise since the 1970s (Figure 1C) and the number of residential or business buildings now threatened by flooding has been rising and will continue to rise.

The last few centuries, and notably the abrupt termination of the Little Ice Age and onset of industrial era warming saw a regime shift in the occurrence of storms along the coast of the western Mediterranean Sea. While we acknowledge that the Little Ice Age climate is different from the climate we are experiencing today, little is known about the future of extreme events in the context of sea level rise and warming Mediterranean surface waters. The mechanisms that cause regime shifts are still not sufficiently well understood to allow accurate predictions of extreme events, or to assess the risk of exposure of human populations in the context of rapidly increasing urbanization and tourism along the Mediterranean coast.

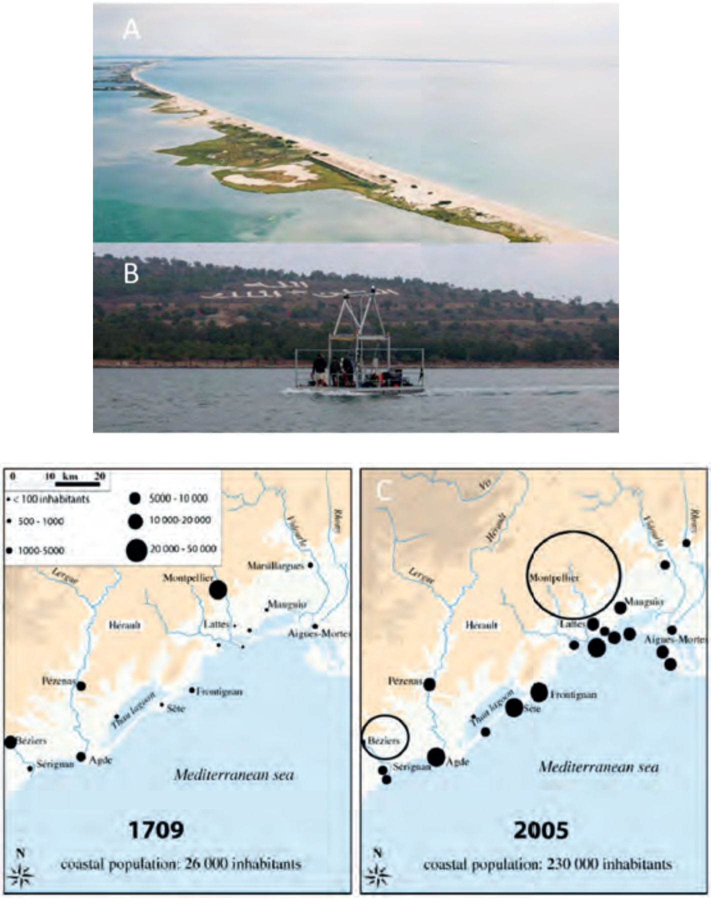


*Figure 1*
*A. Aerial photograph of washover fans (Palavasian lagoons, France).*
*B. The Uwitec platform used in the different lagoons to collect sediment cores.*
*C. The resident population on the coast of the French part of the Mediterranean area has increased by a factor of 15 since 1709 with a dramatic increase since the 1970s. Today, 150 000 people live on the sandy barrier all year round. The area had a 0.2% average probability of being struck by one catastrophic storm per year in the last 2,000 years. This estimate was higher (2%) during the latter half of the Little Ice Age when the risk increased by a factor of 10. The last few centuries have seen a regime shift in the occurrences of storms crossing the coast in the northwestern Mediterranean area (Dezileau et al. 2011).*

The recent reconstruction of sea surface temperature in the NW Mediterranean Sea (Gulf of Lion) revealed strong decadal scale fluctuations (over ~1 °C) associated with cold extremes followed by steep warming of over ~1 °C during the Little Ice Age, i.e. prior to the industrial area (Jalali et al. 2016) (Figure 2A). The occurrence of the severe conditions is thought to be linked to North Atlantic blocking regimes leading to intensified cold Mistral winds blowing in southern France and the NW Mediterranean Sea. According to model simulations, low solar activity during the Little Ice Age created favorable conditions for blocking regimes. During the Medieval Climate Anomaly (1000 – 1200 AD) surface temperatures in the north-western Mediterranean Sea were ~1 °C lower than those at the end of the 20$^{th}$ century.

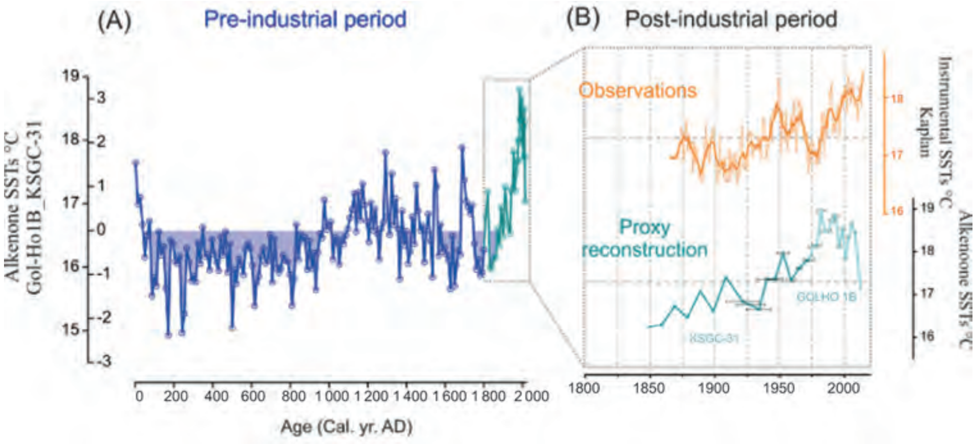


*Figure 2*

*A. Changes in the sea surface temperature in the north-western Mediterranean Sea (Gulf of Lion) over the last 2,000 years derived from alkenones as a temperature proxy.*

*B. Comparison between the proxy reconstruction and instrumental data over the last century.*

The steep rise of ~2 °C in temperature over the last century seen in the proxy reconstruction is in agreement with instrumental data (Figure 2B). This rate of warming is higher than the 0.6 °C observed in the Northern Hemisphere during the same time interval or during the last deglaciation in the western Mediterranean (ca 0.06 °C/century). The post-industrial warming reversal of the pre-industrial long-term cooling, which is also observed in the global ocean surface temperature (McGregor et al., 2015), emphasizes the influence of human activities on climate.

During the MISTRALS/PaleoMeX project, changes in deeper water temperatures were estimated for the first time from proxy analyses conducted on precisely dated deep water corals collected at ~ 400 m in the central and western Mediterranean Sea using a remotely operated vehicle (ROV) (Figure 3AB). According to our results, temperatures were ~2 °C lower during the Little Ice Age but close to modern values in the 19$^{th}$ century. Annually resolved temperature reconstructions between 1950 and 2000 obtained from the shallow water coral *Cladocora caespitosa* in the Tyrrhenian Sea revealed an increase in sea surface temperature of ~+0.023 °C/year, which is in very close agreement with instrumental measurements and the alkenone sea surface temperatures in the Gulf of Lion (see above).

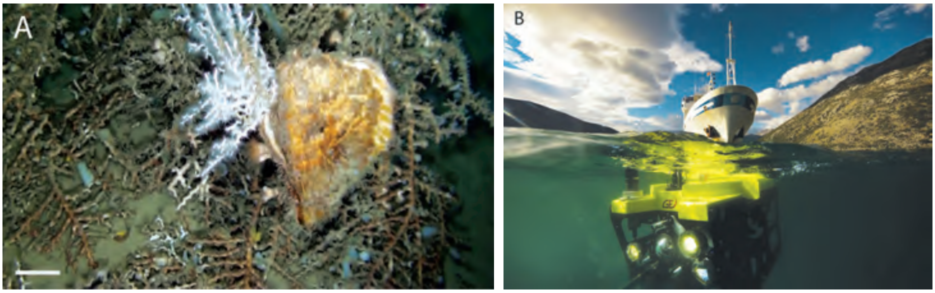


*Figure 3*
*A. Living cold water corals Madrepora oculata and Desmophyllum dianthus growing on a deep-sea giant oyster Neopycnodonte zibrowii collected by a remotely operated vehicle (ROV) in the Sardinia Channel during the RECORD cruise in 2013.*
*B. Hunting for deep sea corals in the Mediterranean Sea on board the R/V Urania. The ROV is maneuvered from the research vessel down to the seafloor, where it searches for samples of coral that preserve the history of climate change.*

Increasing $CO_2$ emissions do not only result in global warming. Penetration of $CO_2$ into the ocean through gas exchange with the atmosphere causes the progressive acidification of both surface and deeper waters. New research on Mediterranean corals to evaluate changes in pH beyond the period of direct observations was also conducted as part of the MISTRALS/PaleoMeX project. Coral derived pH proxy time series over the past 50 years indicate an acidification rate of the Mediterranean surface waters of ~ -0.0014 pH units per year, which is similar to the trend calculated from measured seawater data between 1986 and 2001. This finding confirms the ability of corals to assess changes in the pH of the ocean since the increase in CO emissions needed to estimate the beginning of acidification of the Mediterranean Sea, which represents a major threat for marine calcifying organisms.

## Hydroclimate and vegetation changes in the Mediterranean region

Vegetation is closely linked to regional climate and the pollen produced by plants and tree species has been used by palynologists to reconstruct past air temperature and precipitation. Pollen records have shown that forests recolonized the whole of Europe including the Mediterranean about 10,000 years ago. Over the last 5,000 years, temperate forest progressively retreated northwards or upwards in altitude with the overall increase in dryness over the northern Mediterranean as recorded in southern France, Spain and Italy. In southern France, recurrent swings between beech and oak abundances in the Languedoc hinterland characterized this trend. In the same period in southern Tunisia, the desert progressively expanded (Figure 4AB).

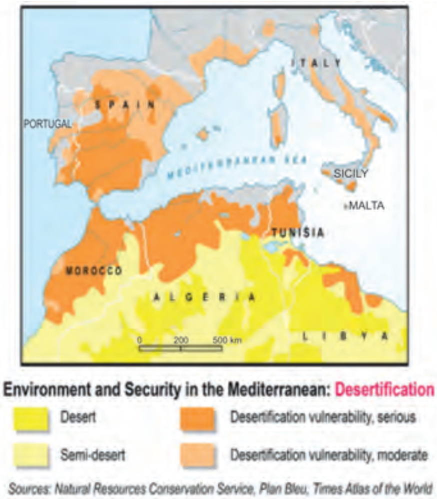


*Figure 4*
*A. Map showing the vulnerability of the west Mediterranean region to desertification (from the Natural Resources Conservation Service).*
*B. An Olive tree submerged by desert sands near Sebkha Boujmel (southern Tunisia).*

Examination of changes in vegetation through pollen assemblages preserved in the sediments clearly shows that long term dryness continues today over the western Mediterranean and even more significantly in the southern Mediterranean borderlands. The species composition of the vegetation cover has been impacted by human activity through the deforestation of northern Mediterranean area. The expansion of desert landscape along the southern rim of the Mediterranean Sea was also notably enhanced by farming, cultivation and grazing from the Bronze Age (4,000 cal BP) to the end of the Iron Age (around 2,000 cal BP), and has further intensified since the beginning of the 20$^{th}$ century (Azuara et al. 2015; Jouadi et al. 2016). The hydrological activity of major Mediterranean rivers was also deeply modified, in particular during deforestation phases when high rates of erosion were revealed by sediment fluxes and by the subsequent increase in the occurrence of floods, as evidenced in the Rhone River basin (Bassetti et al. 2016). Modeling studies using pollen data estimated a decrease of about 50% in the arboreal pollen input in the western Mediterranean lowlands between 6,000 years ago and today (Collins et al. 2012). Furthermore, land registers indicate low forest cover (3% to 13%) in southern France at the end of the 19$^{th}$ century (Koerner et al., 2000). Quantifying vegetation changes is critical to evaluate feedback mechanisms on climate and their consequences for the environment.

Information about past continental temperature and precipitation is also provided by speleothems that form in caves from precipitation waters depending on the location and the weathering of the host rocks. Oxygen isotopes are the most commonly analyzed chemical in speleothems to derive environmental and climatic factors. In some caves, climate information can be linked to human occupation, for example in Gueldaman cave in northern Algeria, one of the few examples in which it is possible to link human history and climate. In this cave, archaeological layers contained numerous prehistoric remains including pottery, bones and charcoal dated by radiocarbon dating (Kherbouche et al. 2014) (Figure 5). Stable oxygen isotopes in the stalagmites in the cave revealed a drought that lasted several centuries between 4,400 and 3,800 years ago, leading to the abandonment of the cave around 4,403 years ago after several thousand years of occupation. This study provides an example of the role that climate may have played in societal reorganization. Several stalagmites that grew in the cave during the Holocene indicate other periods of past climate variations that appear to be synchronous with human occupation.

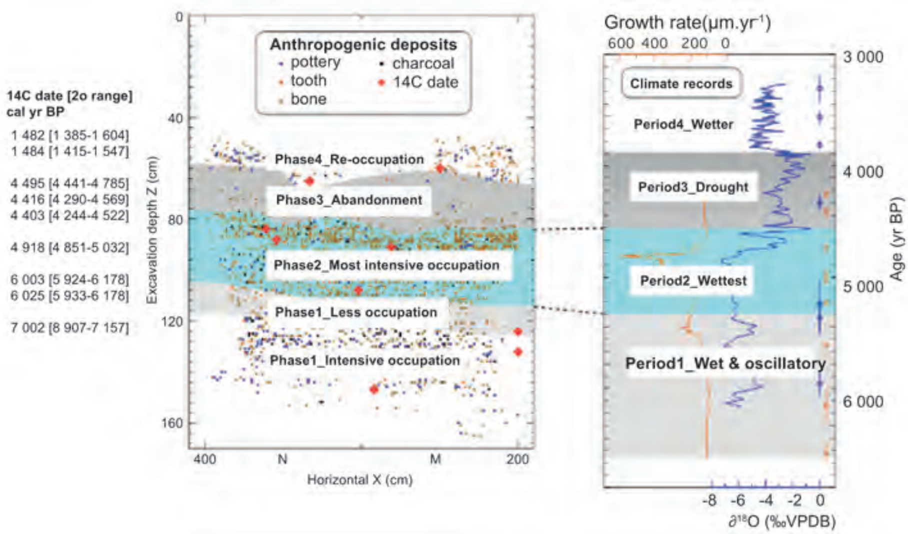


*Figure 5*
*Comparison of evidence of ancient human occupation and past climate change in Gueldaman Cave (from Ruan et al. 2015).*

While the current climate change has encouraged interdisciplinary collaboration to better understand the role that climate may have played in the development of past Mediterranean societies, effective collaboration between disciplines is still a challenge (Izdebski et al. 2016). The study of the occupation of Gueldaman Cave can be seen as a first step towards more integrated efforts between scientists, archeologists and historians the MISTRALS/PaleoMeX project is trying to promote, in the knowledge that, to be efficient, interactions need to be thought out and discussed at the very early stage of the process of the co-construction of the research project. Identifying target sites and designing the strategy has been the guideline for the second phase of MISTRALS/PaleoMeX science plan structured in *Transects* to favor exchanges between fields of expertise.

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Sub-chapter 1.1.3

# Past hydrological variability in the Moroccan Middle Atlas inferred from lakes and lacustrine sediments

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# Introduction

The challenge is to implement research that can estimate the consequences of climate changes in terms of impact on terrestrial environments and resources. Emphasis should be placed on regions dependent on natural resources and for which demographic pressure is strong. Simulations obtained from climate model projections (using different Representative Concentration Pathways (RCPs)) predict that the Mediterranean basin and its southern periphery are particularly vulnerable to water resources and environmental impact (IPCC, AR5, 2013). An annual rainfall decrease by 30% is found for the projection period 2070-2099 (IPCC, AR5, 2013) associated with a decrease in water resources by 30 to 50% (Milano, 2012). In addition, several studies using regional atmospheric models indicate an increase in the precipitation inter-annual variability with extreme events and a spatial heterogeneous signature, superimposed on a decrease in the total precipitation amount (Giorgi and Lionello, 2008; Raible et al. 2010). Currently, regional climate projections are highly sensitive to the climate model used. In particular, spatial resolution as well as local climate conditions seem to impact significantly on the simulations (Jacob et al. 2014).

The Mediterranean region, at the interface between arid and temperate climates with several mountainous areas, is a complex climate system affected by the interactions between mid-latitude and sub-tropical processes. In this context, Morocco, located at the transition between a temperate climate to the North and a tropical climate to the south constitutes a key area for an impact and sensitivity study to global climate changes. The climate is influenced by the Atlantic Ocean, the Mediterranean Sea and the Sahara, together with a very steep orography in the Atlas region. The precipitation distribution is therefore characterised by great spatial variability, and exhibits a marked seasonality, a strong inter-annual variability (Ouda et al. 2005) and in general a pronounced gradient from north to south and west to east. At a broader scale, Morocco is located on the subtropical subsidence path and between the Acores High and the Saharan Low (Agoussine, 2003). Several studies have also identified strong links with inter-annual precipitation variability and NAO index (Knippertz, 2003) as well as remote climate modes (Esper et al. 2007).

Continental climate variability at a local/regional scale, if it is to be integrated in climate predictions, needs to be supported by long-term observation. Meteorological stations in Morocco provide climatic data mainly for the last 40 years with only a few stations located in the mountainous region (Tramblay et al. 2012; 2013; Driouech et al. 2010). This climate database is also supported by the IAEA network providing stations for which isotope tracers have been applied to daily/monthly rain and water vapour samples over 2 to 3 years between 2000 and 2004. Besides the poor coverage of instrumented areas, lacustrine systems can provide a climatic data set that offers access to short and long-term time series of climate parameters when knowledge of modern lake water balance is combined with lacustrine sedimentary-climate records. Lake sediment records ideally provide high resolution climate/environmental information of the last 10,000 years (Magny et al. 2013). This time interval (corresponding to the Holocene) is a key period to investigate short and long-term climate variability and to improve prediction in a warming climate.

In this study we present an integrated approach focusing on a mountainous lake (Aguelmam Azigza). The modern lake system study is based on site monitoring (2012-2016) and available regional hydro-climatic data. These data show that lake level changes during the instrumented period were mainly driven by precipitation following the high inter-annual variability. These data are then compared with accurately dated short sediment cores retrieved in the same lake. Micro-scale geochemical and sedimentological analyses of these sequences enable us to identify various sedimentary facies that can be linked with periods of high (low) lake levels over the past decades.

## Study area

The Moroccan Middle Atlas is an intra-continental mountain range belonging to the Atlasic system (Choubert and Marcais, 1952). It comprises two morpho-structural units: the tabular Middle Atlas in the Northwest and the folded Middle Atlas in the southeast separated by the Northern Middle Atlas fault (Martin, 1981). The study area is located in the Ajdir plateau of the tabular Middle Atlas. Its structure consists of landscapes of elevated Jurassic limestone and dolomite lying over Triassic argilites and Paleozoic basement units (Lepoutre and Martin, 1967). It is close to the Oum R'Bia springs and belongs to the Oum R'Bia watershed, one of the most important fluvial system in Morocco with a catchment area of about 48000 km$^2$ (Figure 1a).

The climate in the Middle Atlas is of a Mediterranean sub-humid type, characterised by wet winters and dry summers (Martin, 1981). This particular climate results essentially from its altitudinal position, its geographical position and its exposure to marine influences (Atlantic and Mediterranean). Mean annual temperature (MAT) in the area is about 13°C (with maximum daily values of 35°C and minimum of -4°C). Mean annual precipitation (MAP) is about 900 mm, most of which falls between October and April (Martin, 1981). It is assumed that 20 to 40% of the total rainfall infiltrates. The numerous lakes, caves, rivers and springs that feed the Oum R'Bia river, make the region one of the most important water reservoirs in Morocco.

Long-term daily precipitation and temperature series (Figure 1b) were obtained from the governmental hydrological services of Morocco (ABOER, Tamchachate station, 33°4N, 5°16W, 1685 m asl) in charge of dams and water regulation structures. Most of these stations were installed during the sixties. The raw data

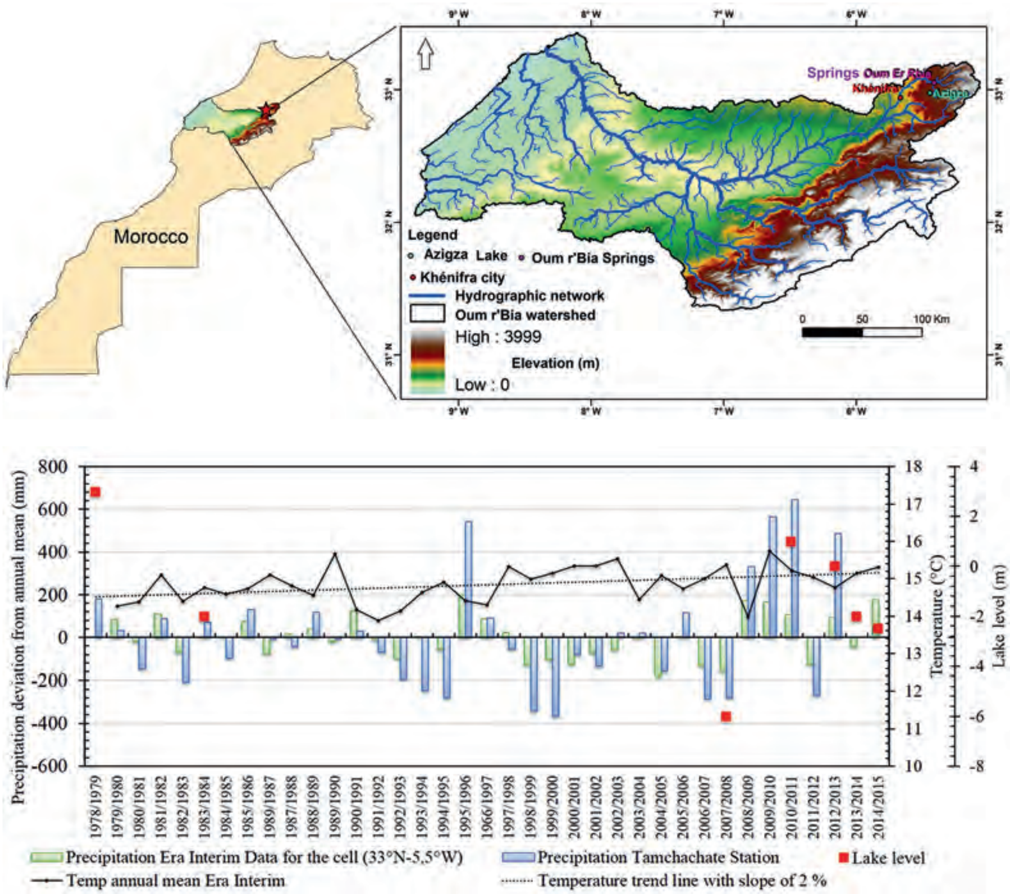


*Figure 1*

*Hydro-climatic context of the study. a: Watershed of the Oum R'bia area.*
*b: Times series of mean annual temperature (MAT) and precipitation (MAP) close to the study area (Tamchachate station, ABOER data; ERA-Interim re-analyses data).*
*Data are expressed as standard deviation to the mean (calculated for the whole period, 1979-2015).*
*Symbols (red) indicate lake levels observed at the study site (Lake Azigza)*
*(compared to our reference level of 2013).*

of the precipitation record have been checked for quality control. For comparison, ERA-Interim re-analyse precipitation and temperature data provided by the ECMWF were used (Dee et al. 2011). The data are available every 3 hours and cover the period from January 1979 to the present with a projected horizontal resolution grid of 0.5°*0.5°. The mean annual air temperature series obtained close to the study site between 1979 and 2015 is about 14.5°C. A long-term trend in the temperature record can be detected toward increasing values (about 2% increase per decade). This has been already documented for several regions in Morocco since 1960's (Driouech et al. 2010). For precipitation, both data sets (ABOER and ERA-Interim) reveal a strong inter-annual variability

(Figure1b), which is one of the most important feature of the Mediterranean climate (Lionello, 2012). Higher average precipitation is recorded at Tamchachate, linked to the orographic influence. Similar inter-annual trends are observed between both sets, despite a smoothing effect for ERA-INTERIM re-analyses data which are based on few stations. The precipitation variability is also marked by extreme hydrological events. Some of them had a large regional impact like in 1995 (violent flood episode in the Ourika valley).

## Hydrological context of Lake Azigza

Aguelmam Azigza Lake (32°58N, 5°26'W, 1544 m asl) is a natural lake, in a tectono-karstic depression along a NW oriented fault line, located at about 30 km east of the city of Khenifra.

The lake has been studied intermittently since 1940. Previous works noticed the relative pristine nature of the lake environment (particularly the Cedar forest) and the low level of human activity in the catchment area. The local vegetation is dominated by Cedar *(Cedrus Atlantica)* and Oak *(Quercus)* woodland formed on calcareous red soils. Physical parameter measurements (temperature profiles) have shown that the lake is monomictic with a winter overturning period (Gayral et Panouse, 1954). This has been confirmed with recent temperature profiles indicating a thermocline at about 8 m water depth during stratification periods (spring, summer and autumn). The lake is fed by diverse springs and sub-surface inflows. Despite the absence of surface outflows, chemical and isotopic signatures of water samples suggest an open system, with a short residence time and diluted water (Benkaddour et al. 2008). Ample evidence of significant lake level changes have been observed (Gayral et Panouse, 1954; Flower et al., 1992; Benkaddour et al. 2008) (Figure 1b). It was suggested that variation in annual rainfall significantly affects the magnitude of water level fluctuations (Flower et al. 1992), although the contribution of groundwater processes in modulating the lake response needs to be considered. Precise information about the timing and causes of these variations is still missing, mainly due to poor data availability.

For this study, a high resolution digital elevation model (DEM) of the lake and its watershed was produced (Adallal, Thesis) (Figure 2a). The lake's surface is $0.48*10^6$ m$^2$ and its volume is $6.91*10^6$ m$^3$. The watershed (automatically delineated from the DEM using the ArcHydro extension of ArcMap) has a surface of $10.16*10^6$ m$^2$, about twenty times the lake surface. The morphometry of the lake shows a mean depth of 26 m and a maximum depth of 42 m in the eastern part of the basin characterised by steep slopes compared to the western part (Figure 2a). Today, the lake has no surface outflow but evidence for a former outlet has been observed on the NW shore, probably linked to past high lake level periods.

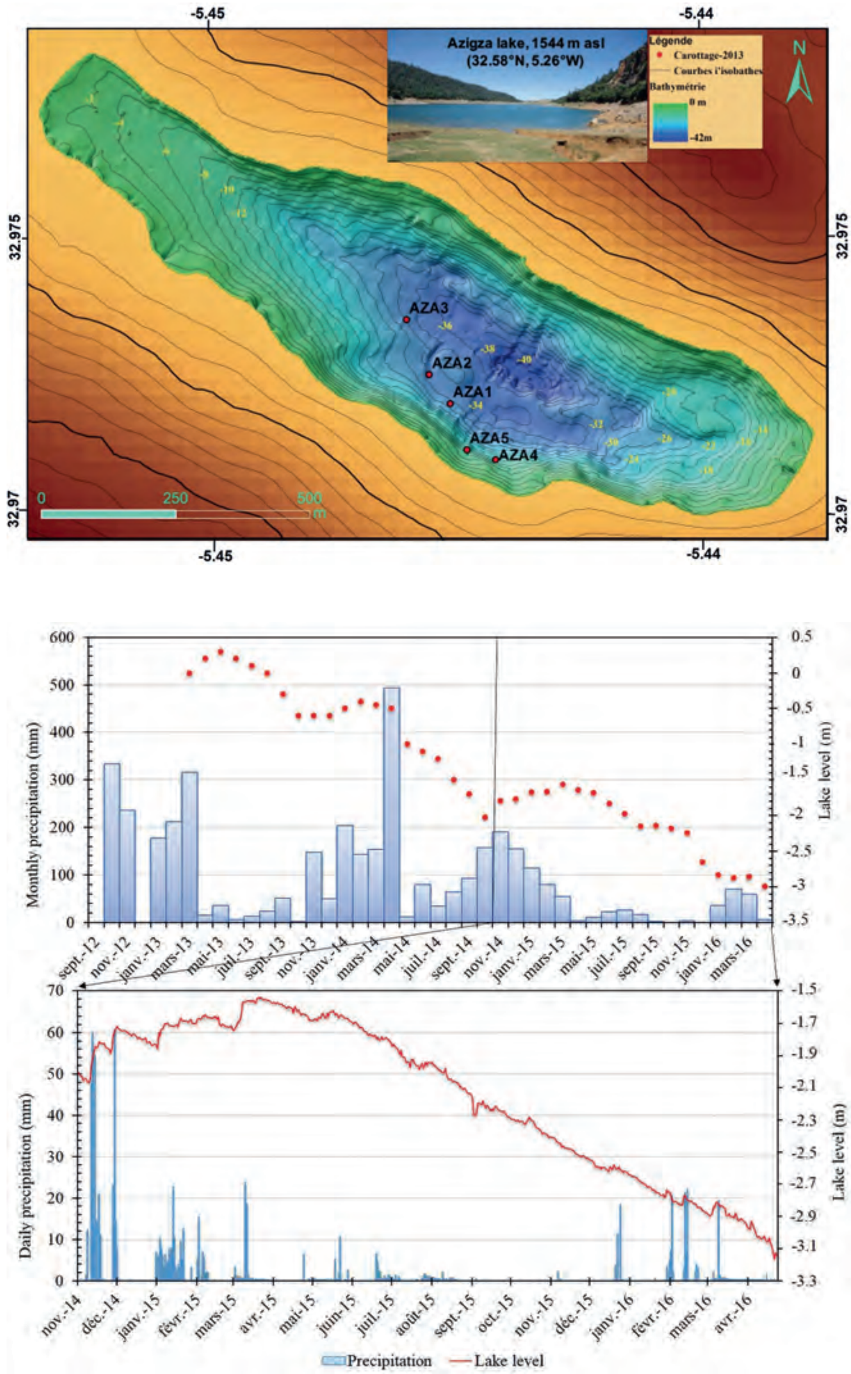


*Figure 2*

*Hydro-climatic data from Lake Azigza.*

*a: High-resolution digital elevation model (DEM) of the lake watershed and bathymetry.*

*b: Monthly and daily precipitation (2012-2016) and lake level (2013-2016) monitoring.*

Since October 2012, a monthly sampling of precipitation (using a rain gauge), lake and spring waters has been undertaken for hydro-chemical and isotopic analyses. In April 2013, monthly measurements of Azigza lake level have been manually measured using a reference gauge (Figure 2b). After November 2014, the installation of a data logger and a meteorological station at Lake Azigza enabled us to collect daily measurements. The data logger was anchored in the eastern part of the basin in order to measure water pressure, temperature and conductivity at 2.6 m under the water surface. Lake level is obtained by correcting the water pressure data from the atmospheric pressure measured at the same place. Other atmospheric parameters were measured with the meteorological station (precipitation, temperature, evaporation, humidity, solar radiation and wind speed) (Figure 2b).

For the instrumented period, the MAP is estimated at about 1100 mm/yr**.** The daily data reveal a strong link between precipitation and lake level over an annual cycle, which increases during the rainy season (November to February) and decreases during the dry period, with an annual amplitude of 0.5 m. In addition, the lake level responds rapidly to precipitation events with, for example, a mean increase of about 0.15 m (in a few days) followed by a relaxing period when rainfall stops mainly controlled by evaporation and groundwater outflow.

Over and above these changes, we also observed a long-term trend with a lake level decline of about 3 m since April 2013. As already mentioned, lake level fluctuations of several meters have been documented from the survey of former lake level terraces. These results found that low lake level for the early 50's coincided with a sharp decline in annual rainfall (Flower et al. 1992). Historical aerial photographs (obtained from Direction de Cartographie, Rabat, Morocco) and historical lake level observations (Flower et al. 1992; Benkaddour et al. 2008) have been compared to our reference lake level (between 1979 and the present). The data suggest that the lake level fluctuations follow inter-annual variations of precipitation (Figure 1b). It is noticeable that the high lake level reported in 1979-1980 (Figure 1b) follows a rainy period in 1977, 1978 and 1979 as recorded at Tamchachate Station (not shown). Our monthly monitoring of the physico-chemical properties of the lake system (lake, wells, springs) (2012-2014) indicate a significant contribution of groundwater flows in the lake water budget. For example, conductivity data (not shown) do not record any trend apart from the seasonal variability despite the lake level decline. Indeed, the lake water remains fresh even in the absence of surface outflow, in line with previous results (Benkaddour et al. 2008). However, the contribution of this groundwater outflow to the long-term lake level fluctuations still needs to be estimated.

# Hydro-sedimentlogical context

In spring 2013, several short sediment cores from Lake Azigza were retrieved using the UWITEC gravity recovering system. Cores from shallow (16 m water depth) and deep water (30 m water depth) locations were obtained (Figure 2a). The cores were split longitudinally into two halves and after lithological description were used for multi proxy analyses. In general, the sedimentary sequences were composed of unconsolidated light-brown to dark, partly laminated clastic sediments and endogenic carbonates and few transition metal oxides. The cores AZA-13-3 (90 cm long) and AZA-13-1 (78 cm long) retrieved in the deeper basin were first imaged and measured for chemical composition in an X-Ray fluorescence (XRF) ITRAX core scanner (Cox Analytical System) at CEREGE. Using a Molybdenum X-ray source, a suite a chemical element was semi-quantitatively determined (at 40 kV, 30 mA, and an exposure time of 15s). This method provides high-resolution (1mm step) records of six elements (Ca, Fe, Ti, K, Si, Mn).

Thin sections performed at CEREGE for core AZA-13-3 allow for micro-scale observations of the sedimentary facies using a microscopic approach and semi-quantitative analysis of elements using energy dispersive technique (EDS) coupled with a scanning electron microscope (SEM). The elemental mapping of each facies is then linked to the mineralogy and sedimentary characteristics of the sample in order to improve interpretation of XRF signals (Jouve et al. 2013).

The chronological framework of core AZA-13-3 was derived using the $^{210}Pb$ and $^{137}Cs$ activity- depth profiles. The radionuclides content of the bulk sediment was measured for 13 samples (for the uppermost 40 cm of core AZA-13-3) by gamma spectrometry at Géosciences, Montpellier. Concentration of $^{137}Cs$ clearly identifies the AD 1963 peak due to atmospheric nuclear tests and the associated radionuclides fallout (Cambray et al. 1989) (Figure 3a). Sediment accumulation rates estimations using $^{210}Pb$-excess and/or $^{137}Cs$ concentrations give similar results of about 5 mm/year. Considering a continuous sedimentation rate we tentatively estimate that the deep basin sedimentary sequences cover approximately the last 150 years, given that the age model needs to be improved.

Micro-scale analyses of thin section of sediments revealed three main facies in core AZA-13-1. The first is a mixing of clastic (quartz) and authigenic (calcite) sediments with thin laminations of calcitic shells of ostracods and bivalves, and wood fragments (Facies 1) (Figure 3b). The second is composed of a mixing of clastic and authigenic sediments with few millimetric calcitic shells of ostracods and bivalves without wood fragments (Facies 2). Facies 1 and 2 repeated several times along the sequence while Facies 3 is only present in the upper part of the sequence. It is composed of a mixing of clastic and authigenic sediments that integrate a critical amount of authigenic minerals, such as gypsum, pyrite and phosphates, inconsistently deposited on Facies 1.

Facies 1 is interpreted as a proxy of higher superficial runoff during high lake levels. During increased runoff activity, and when the shoreline is close to the cedar forest, calcitic shells and wood fragments can be mobilized from the littoral zone. Facies 2 reflects reduced runoff activity associated with low lake levels. Indeed, when the shoreline is closer to the coring site, coarser

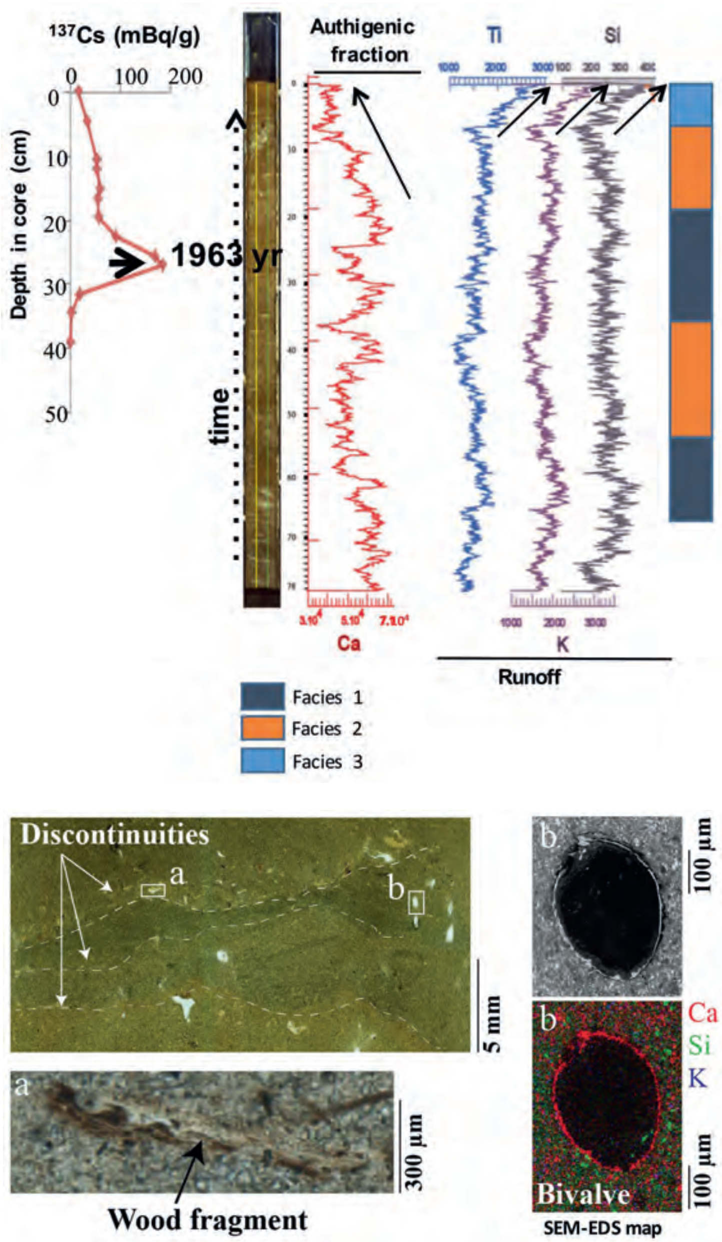


*Figure 3*
*Geochemical composition and sedimentary structures of Azigza lake sediment cores.*
*a: Age model and XRF measurements (Ca, Ti, K, Si)*
*for core AZA-13-3 (N32°58,418; W5°26,708; 32 m water depth).*
*b: Micro-facies structures of facies 1 at 34 cm in core AZA-13-1*
*(N32°58,332; W5°26,659; 30 m water depth) corresponding to a high lake level period*
*(derived from SEM-EDS measurements on indurated blocks of sediment).*

calcitic shells can be moved from the littoral zone to the deep basin. In this case, less intense superficial runoff prevents the transport of wood fragments to the basin.

In agreement with the sedimentation rate derived from the age model, Facies 3 is interpreted as the sedimentary deposit derived from the refilling period of the shallow basin in 2009, following a period of low rainfall (Figure 1b). When the lake level was rising, the superficial runoff carried authigenic particles from the shallow to the deep basin throughout small rivers (visible in the bathymetry, Figure 2a and Jouve et al. in prep). A fast lake level rise could have led to water column stratification and suboxic/anoxic conditions at the water/sediment interface and thus the precipitation of pyrite.

These interpretations are consistent with XRF data, since elemental proxies of superficial runoff (Si, Ti, K and Fe) are higher/lower associated with Facies 1 and 3/Facies 2 (Figure 3a). Moreover, using the age model, periods of high/low lake levels are coeval with periods of higher/lower annual precipitation close to our study area (Figure 1b). Since 1963, two periods of high (from the 60s to the 70s, and since 2009) and one period of low lake level stand (from the 80's to 2008) seems to be synchronous with the appearance of Facies 1/2 respectively.



# Conclusion and perspectives

Several studies have already highlighted the significant impact of human and climatic factors in the Middle Atlas lake systems at various spatio-temporal scales (Lamb et al. 1995; Cheddadi et al. 1998; Rhoujatti et al. 2010; Damnati et al. 2012 among others). These approaches, while indicating the vulnerability and sensitivity of these lakes suffer from poor current characterisation of these hydro-systems needed for a better interpretation of sedimentary records in term of past hydrological variability. Long-term site survey is essential to conduct research dealing with the environmental impact of global climate change in vulnerable remote areas.

At Lake Azigza, our site monitoring (2012-2016) confirmed the strong link between lake level fluctuations and precipitation variability at daily, monthly and annual steps. This data set will definitively help to understand the long-term decreasing trend of the lake level as observed during the instrumented period. Indeed, the understanding of the hydrological behaviour of the lake requires the quantification of the groundwater contribution to the lake water balance. This is an ongoing study in which a water balance model is coupled with water isotopes (Adallal et al. in prep.). The simulation of the lake level and lake isotopic composition at daily and monthly steps compared to the measured data set will provide a quantified relation between climate, groundwater inflows and outflows, and lake level variations. Finally, our approach has the potential to provide quantitative past lake level reconstructions using the hydrological model forced by historical precipitation times series. The same approach should be tested with precipitation simulations obtained from high resolution regional climate model projections.

The micro-scale studies of the sedimentary lake deposits revealed that sedimentary structures and geochemical composition can be interpreted as a proxy for runoff intensity. The improvement of the dating of the cores will allow for the extension of the sedimentary record over the last 150 years. A calibration of the proxy with the climatic data will be tested and used to reconstruct runoff intensity changes (linked to precipitation extreme events) over the last 150 years, beyond the instrumental period. Interestingly, Flower et al. (1992) did not find obvious records of the recent lake fluctuations in deep-water sediment cores (from coarse grain size measurements) and concluded with fairly stable soil erosion rates. The approach conducted in this project shows that micro-scale observations can bring valuable additional sedimentary information linked to the hydro-sedimentary behaviour of the lake.

The integration of modern lake system knowledge (through site instrumentation and modelling) with lacustrine sedimentary climate records from the same site will provide new insights into the study of continental hydrological variability at various time scales. It will enable us to evaluate the imprint of human activities *vs* climate factors at decadal scale for the last millennia and provide keys to future environmental management and preservation purposes.

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Chapter 2

# Climate change in the Mediterranean region

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## Abstract

The Mediterranean region has been identified as one of the most sensitive regions in the world to climate change. The high sensitivity of the hydrological cycle to climate change is a consequence of both the location of the region in a transition zone between a temperate climate in the mid-latitudes and the hotter-drier North African climate and its specific physiographic features, i.e. a nearly enclosed sea surrounded by mountains and highly urbanized coastal areas. These climatic, topographical and anthropogenic factors also explain the marked spatial and temporal variability of the atmospheric, oceanic and hydrological conditions in the Mediterranean region.

Analyses of observation-based data show that the Mediterranean region has tended to be warmer and drier during the last half century, associated with an increase in evaporation and a decrease in runoff. Global and regional climate model projections indicate that warming and drying will likely continue, with the amplitude of the changes after 2050 being highly dependent on the emission scenario. The climate models also predict a general increase in temperature extremes for the end of the 21st century. However, the exact spatial distribution of changes in temperature and much more in precipitation remains uncertain.

Both global and regional climate models clearly predict warming of the Mediterranean Sea surface propagating towards the deeper layers. The thermohaline circulation is expected to change under the influence of warming as well as with the uncertain changes in salinity, an issue which is still under debate. In any case, these future changes will influence the exchange of water and heat at the Strait of Gibraltar and consequently heat and salinity in the deep layers of the North Atlantic Ocean, whose source is the Mediterranean Sea. However the models do not agree on the future thermohaline circulation or on exchanges between the Mediterranean Sea and the Atlantic Ocean.

# Résumé

La région méditerranéenne est reconnue comme étant une des régions au monde particulièrement sensible au changement climatique. Plusieurs raisons expliquent cette forte sensibilité du cycle de l'eau en Méditerranée au changement climatique. Tout d'abord, le bassin méditerranéen se trouve dans une zone de transition entre le climat tempéré des latitudes moyennes et le climat plus chaud et sec de l'Afrique du Nord. Un autre facteur d'explication provient de ses caractéristiques géographiques, i.e. une mer semi-fermée entourée de montagnes et de régions littorales très urbanisées. Ces facteurs climatiques, géographiques et anthropiques contribuent aussi à la forte variabilité spatiale et temporelle des conditions climatiques, océaniques et hydrologiques rencontrées en Méditerranée.

L'analyse des tendances observées des moyennes annuelles sur le dernier demi-siècle montre des évolutions des composantes du cycle de l'eau en Méditerranée avec, globalement en Méditerranée, une augmentation de la température, une diminution des précipitations et des apports des fleuves à la mer, et une augmentation de l'évaporation. Les projections climatiques des modèles globaux ou régionaux du climat indiquent que ce réchauffement et assèchement va se poursuivre, avec une amplitude de ces changements qui dépend principalement après 2050 du scénario d'émission. Les projections climatiques indiquent aussi une augmentation en fréquence et intensité des vagues de chaleur. Néanmoins, la distribution spatiale détaillée des changements en température, et encore plus des changements en précipitation, demeure encore incertaine.

Les modèles de climat prévoient clairement une augmentation de la température de la mer en surface sous l'effet du changement climatique, qui se propage aux couches profondes océaniques. Il est attendu que la circulation thermohaline de la Méditerranée va évoluer sous l'effet de ce réchauffement de la mer et des changements encore incertains de la salinité. Les échanges de chaleur et d'eau au détroit de Gibraltar devraient aussi être modifiés en conséquence, et donc la source de chaleur et de sel que représente la mer Méditerranée pour l'Atlantique Nord. Il n'y a cependant pas à ce jour de consensus entre les modèles sur les caractéristiques d'évolution de la circulation thermohaline de la Méditerranée et des échanges avec l'Océan Atlantique.

Sub-chapter 1.2.1

# The water cycle in the Mediterranean

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## Introduction

The Mediterranean region has quite a unique character that results both from physiographic conditions and historical and societal developments. Because of the latitude range it covers, the Mediterranean region is a transition area under the influence of both the temperate mid-latitude climate and the hotter-drier North-African climate. In addition, the region features a nearly enclosed sea surrounded by highly urbanized littorals and mountains in which numerous rivers have their source. This results in interactions and feedback between ocean-atmosphere-land processes that play a prominent role in the climate and hydrological cycle, including in the high-impact weather events that frequently affect the region.

The hydrological Mediterranean basin is also characterized by a strong coastal component. Only 21 catchments have an area of more than 10,000 km$^2$, and they represent only 42% of the total Mediterranean basin. The remaining part of the hydrological Mediterranean basin is made up of many small to medium size watersheds. Most of these small rivers are intermittent as well as ephemeral but can become powerful torrential rivers during flash-flooding episodes in fall and winter. The water resource is a major concern for a large part of the Mediterranean basin. Freshwater is rare and unevenly distributed in time and space, and the current situation is worsening due to increasing water demands related to population growth and economic development as well as to climate change.

The Mediterranean region in fact concentrates all the main natural risks linked with the water cycle, including heavy precipitation leading to flash floods, strong winds and associated large swells and storm surges, heatwaves and droughts accompanied by forest fires. Such natural hazards affect the populations living in the area. Accurate forecasting of such high-impact weather events is still challenging and there are large uncertainties in the prediction of their evolution under climate change, especially precipitation extremes.

The hydrological cycle in the Mediterranean region is thus a key scientific, environmental and socio-economic issue in a large region that includes southern Europe, North Africa and the Middle East, which motivated the 2010 launch of the 10-year HyMeX experimental research program dedicated to the hydrological cycle in the Mediterranean region (see Box 1).

The following sections of this sub-chapter describe the main characteristics of the Mediterranean climate, of the Mediterranean Sea, and of the continental hydrology, their variability and trends over recent decades. Sub-chapters 1.2.2 and 1.2.3 present the results of the future climate projections under emission scenarios for the Mediterranean climate and the Mediterranean Sea, respectively. The variability, trends and future changes in hydrometeorological extremes under climate change are discussed in Chapter 1.3.



### Box 1
### HyMeX – A research program on the water cycle in the Mediterranean

The overarching objectives of the Hydrological Cycle in Mediterranean Experiment (HyMeX) program are to improve our understanding of the water cycle, with emphasis on the predictability and frequency of high-impact weather events, and to evaluate the social and economic vulnerability and capacity of the Mediterranean territories and citizens to adapt to these extreme events (www.hymex.org, Drobinski et al. 2014). HyMeX is an international and interdisciplinary program involving about 350 scientists from about 20 countries.

The 10-year HyMeX program consists in observing and modeling the atmosphere/sea/continental surface system from the event to the climate scales. The HyMeX observation component includes (i) heavily instrumented special observation periods of a few months to provide detailed and specific observations to analyze key processes and (ii) longer observation periods repetitively or routinely collecting observations to monitor long-term water cycle processes and rare events such as flash-floods over a few specific instrumented watersheds. Two special observation periods, involving research aircraft and airborne instruments, instrumented platforms at sea and numerous ground-based research instruments, took place in northwestern Mediterranean to document heavy precipitation and flash-floods in the fall, 2012 (Fig. 1, Ducrocq et al. 2014) and ocean response to strong regional winds in late winter, 2013. The exploitation of the rich database (more than 450 datasets) obtained thanks to successful field campaigns, and the modelling components, has already produced numerous results, with more than 300 peer-reviewed articles published in international scientific journals. The outcomes of the program include the improvement of the numerical weather forecasting systems, the forecasting of flash-floods and the production of MED-CORDEX regional climate projections for the Mediterranean area for impact studies (Ruti et al. 2016), among others.

*Figure 1*
*Some examples of research instruments deployed in the fall, 2012 in France, Spain, and Italy.*
*Top row: ATR42 (left) and Falcon20 (right) from the French operator SAFIRE of environmental research aircraft (CNRS/INSU, Météo-France, CNES).*
*Middle row: X-band radar from ETHZ deployed in the Cévennes (left), instrumented Météo-France buoy in the northern Mediterranean (center); Radiosonde launches from the CNRM mobile station (right).*
*Bottom row: Non-contact discharge radar (left), CTD rosette deployment at sea (right).*

*In France, the program is mainly funded by the MISTRALS meta-program (CNRS, Météo-France, IRSTEA, INRA), the French National Research Agency (ANR), CNES, and the territorial collectivity of Corsica.*

# Mediterranean climate

## Temperature and precipitation variability

The climatology of the Mediterranean region is characterized by dry summers frequently associated with very long drought periods, followed by fall and winter rainfall events that are mostly very intense. It is not rare that total monthly precipitation at a specific location falls in only few hours (during thunderstorms). Mean summer temperatures show a gradient from north to south with mean temperatures exceeding 30 °C in the southeast (Ulbrich et al. 2013). Summer in southern Mediterranean regions is characterized by high temperatures and lack of rain, leading to drought and marked arid conditions. Total precipitation values show high spatial and temporal variability. Mean annual precipitation amounts range from less than 200 mm/year (North Africa, Arabian Peninsula) up to 2,000 mm/year over some northern mountainous areas. Winter half-year precipitation accounts for between 30% (western and northern Mediterranean area) and 80% (eastern and southeastern parts) of the annual total precipitation (Xoplaki et al. 2004).

The high spatial and temporal variability of the seasonal mean temperature and total precipitation is explained by several features. First, the Mediterranean region is located at the southeastern limit of the North Atlantic storm tracks, and is thus particularly sensitive to interannual displacement of the paths of mid-latitude cyclones that can affect precipitation over the region. The Mediterranean climate is also influenced by tropical and subtropical systems (tropical cyclones, Asian summer monsoon, etc.). All these influences result in marked variability. In addition, the complex morphology of the Mediterranean region, including high mountain ridges surrounding the coast and sharp orographic features, islands and peninsulas, leads to much sharper and smaller-scale climatic features than over other ocean basins. The Mediterranean Sea is also a source of moisture and heat for the mesoscale atmospheric circulation that can evolve into high-impact weather systems such as heavy precipitation thunderstorms, cyclogenesis and wind storms.

## Observed trends

Observed trends indicate a general tendency for annual mean conditions to become warmer and drier. Indeed, observations and the CMIP5 global climate simulations show progressive warming of the land surface air temperature since the 1960s. Using the CMIP5 multi-model and observational data, Mariotti et al. (2015) estimated the annual mean surface air temperature trend in the Mediterranean region over the 1960-2005 period to be 0.19-0.25 °C per decade. The trend for the summer months is higher, over 0.3 °C per decade. The annual mean precipitation trend has been estimated to be about -0.6 $10^{-2}$ mm/day/decade for the last century over the entire Mediterranean region. These observed long term trends are combined with marked decadal and interannual variability.

# Mediterranean Sea

## Characteristics

The Mediterranean Sea is a semi-enclosed basin connected with the Atlantic Ocean through the Gibraltar Strait and with the Black Sea through the Dardanelles Strait. The surrounding orography tends to produce cold dry northern regional winds (Mistral, Tramontane, Bora, etc.) over the Mediterranean Sea, leading to high losses of heat and of freshwater by evaporation and latent heat transfer. These specific features strongly influence the water budget and the thermohaline circulation of the Mediterranean Sea. Indeed, the Mediterranean Sea has a negative water budget over a multi-year period: the loss to the atmosphere by evaporation is larger than gains due to precipitation and runoff from the rivers. This freshwater deficit is offset by exchanges through the narrow and shallow Strait of Gibraltar, where the inflow is composed of relatively warm and low-salinity upper water, while the outflow to the Atlantic Ocean is relatively cooler and saltier. Light low salinity water from the Atlantic is transformed into denser water through interaction with the low-level atmosphere and deep ocean convection that renew Mediterranean waters at intermediate and deep levels, and generate the thermohaline circulation in the Mediterranean Sea. The formation of deep ocean convection takes place preferentially in the Gulf of Lion, the Adriatic, the south Aegean and the north-east Levantine, regions under the influence of regional winds like the Mistral in the Gulf of Lion. Ocean convection produces deep vertical mixing processes that provide oxygen to the deepest part of the water column and consequently have major impacts on marine ecosystems.

## Observed trends

Estimation of trends using observations of the ocean is much less certain than estimation of trends over land, as series of observations are fewer and not always sufficiently reliable due to sampling errors or temporal homogeneity issues. This justified the setting up of additional long-term ocean observatories such as the MOOSE research observatory (see Box 2). Still, analyses of the trends observed in the Mediterranean Sea in recent decades tend to show a marked increase in the temperature of the deep layer from the mid-1980s as well an increase in salinity. Observations of sea surface temperatures show an increase over the last half-century (Sevault et al. 2014), with rates of increase estimated from different observation datasets for the 1979–2006 period in the range of 0.2–0.3 °C per decade (Mariotti, 2010). Concerning surface salinity, which displays decadal variability, no significant change was observed in the eastern basin, with possibly a small increase in the western Mediterranean (Ulbrich et al., 2013).

Sanchez-Gomez et al. (2011) compared the heat and water budgets of the Mediterranean Sea based on state-of-the-art observational datasets and revealed a wide range of uncertainty. However, the datasets showed an overall increase in evaporation from the sea during the last half-century, with a decrease up until the mid-1970s followed by an increase, thereafter associated with the increase in sea surface temperature (Mariotti, 2010). Observed precipitation estimates over the Mediterranean Sea are very uncertain, which makes it difficult to produce evidence for robust trends. Yet these estimates have shown no significant trend over the whole Mediterranean Sea in recent decades.

### Box 2
### MOOSE - An example of research observatories

Despite intensive research efforts in the Mediterranean Sea over more than a century, an integrated view of its evolution, in the framework of climate change and anthropogenic pressures is still lacking. In this context, a Mediterranean Ocean Observing System for the Environment (MOOSE) was set up as an interactive, distributed and integrated observatory of the north-western Mediterranean Sea to detect and identify long-term changes in the Mediterranean Sea and its ecosystems. MOOSE, built as a multi-scale observation network, is based on a multisite system of continental-shelf and deep-sea fixed stations as well as Lagrangian and mobile platforms to observe the spatio-temporal variability of interactions between the coastal-open ocean and the ocean-atmosphere components. The long term aims of the observatory (Fig. 2) are (i) to monitor the mesoscale circulation in the north-western Mediterranean Sea; (ii) to qualify and quantify river inputs; (iii) to observe and understand the nutrient and gas (O2 and CO2) dynamics in the NW Mediterranean Sea in relation with physical ocean processes and anthropogenic/natural inputs (atmospheric and continental); (iv) systematic end-to-end monitoring, including of prokaryotic communities, phytoplankton, micro- and meso-zooplankton, in relation with environmental parameters to provide an overview of the evolution of biodiversity.

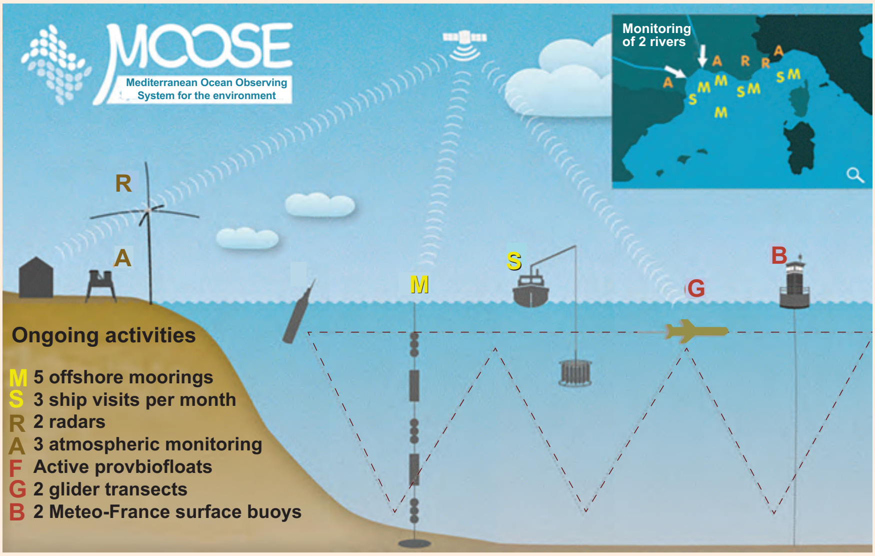


*Figure 2*
*MOOSE set-up.*

Data obtained during the first phase of MOOSE (2011-2015) allowed us to obtain new insight into the interaction of dense shelf water cascading with open-sea convection, their connection with peculiar atmospheric circulation patterns, and their impact on the alteration of deep water characteristics at basin scale. In deep water, a significant increase was observed in the nitrogen:phosphorus ratio, together with a clear decrease in the concentration of oxygen (1.2 µmol/dm3/yr) revealing some changes in biogeochemical components of the Mediterranean Sea.

The MOOSE network is a solid observation service for research into the environment, which is able to provide operational service for the timely, continuous and sustainable delivery of high quality environmental data and information products, related to the northwestern Mediterranean environment.

*The MOOSE network is primary funded by the French National Research Center (CNRS-INSU) and the Alliance Allenvi.*



# Continental hydrological cycle

## Characteristics

Hydrological processes are highly variable in time and space, due to the high variability of the rainfall regime, the complexity of the topography, and the geological, soil and land use characteristics. Most Mediterranean rivers have maximum discharges between February and May and minimum discharges in summer, due to reduced precipitation, elevated temperatures and the associated evapotranspiration in the summer season. Evapotranspiration over land is a key process in the annual continental hydrological cycle, representing between 50% and 80% of the total annual rainfall. Ranked according to annual water discharge, the 10 largest rivers flowing into the Mediterranean Sea are the Rhône, Po, DrinBuna, Nile, Neretva, Ebro, Tiber, Adige Seyhan and Ceyhan rivers, which together account for about half the average freshwater input to the Mediterranean Sea by rivers (Ludwig et al. 2009). The differences between low and high water discharge can be extreme, in particular in the numerous small to medium watersheds most of whose water is collected during short-duration floods. In space, hydrological regimes depend on geographical and anthropogenic factors such as basin size, topographic position (mountainous versus plain), the hydrogeological and aquifer systems (e.g. karstic regions), urbanization, the role of dams and reservoirs (e.g. Asswan), lakes (e.g. the more than 1,000 artificial lakes in Tunisia), human activities (irrigation, farming or industrial activities, hydroelectricity), etc.

## Observed trends

Except for the two largest rivers in the north (the Rhône and the Po) for which no trends have been observed, Mediterranean river discharges are decreasing, with a reduction of at least 20% in freshwater inputs to the Mediterranean Sea between 1960 and 2000 (Ludwig et al. 2009). This decrease is mainly due to the reduction in annual precipitation associated with climate change, and the construction of dams, which may have further reduced discharge. The biggest decrease is indeed observed in rivers that have been affected by the construction of dams such as the River Ebro in Spain and the Moulouya River in Morocco. Lespisnas et al. (2010) studied changes in discharge of smaller coastal rivers and found that the mean annual water discharge in their entire study region (southern France) decreased by about 20% between 1965 and 2004. As they found no clear trend in annual precipitation over the region, the decrease in water discharge is likely to be the result of the rise in temperature causing the switch from snowfall to rainfall at high altitudes and from the drop in groundwater levels, which are also partly explained by the rise in temperature. In a recent study (Zampieri et al., 2015), a consistent earlier spring discharge peak of more than three weeks per century has been found for the Rhône and Po.

This shift in the river discharge of these two largest rivers might, in turn, have implications for the hydrological cycle of the whole region, or at least a large part of it.

# Conclusion

Analyses of long-term trends in the Mediterranean region show that annual mean conditions tend to be warmer and drier, with an increase in evaporation and a decrease in runoff. However, there is high spatial and temporal variability of the atmospheric, ocean and hydrological conditions due to the climate, topographical and anthropogenic factors that are specific to the Mediterranean.

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# The climate of the Mediterranean regions in the future climate projections

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## Introduction

Giorgi (2006) defined hot-spots as the most sensitive regions to climate change. On the basis of a regional climate change index (RCCI) calculated from temperature and precipitation projections, the Mediterranean region was revealed to be one of the most prominent hot-spots over the globe. Considering the last global climate change projections in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013), the singularity of the region, particularly for a future large reduction of precipitation, was confirmed, as illustrated in figure 1. This figure reproduces the projected average percentage change in precipitation in winter (December-January-February) and in summer (June-July-August), under the conditions of the high emission RCP8.5 scenario, for two 20-year periods in the middle and at the end of this century compared to the period 1985-2005. It clearly shows that the Mediterranean region could be affected by a decrease in precipitation in both seasons, becoming more significant with time. This could occur while other regions, particularly those at the same latitude, do not undergo a change that is distinguishable from climate variability due to internal processes of the climate system.

This great sensitivity to climate change can be understood as a consequence of the location of the region in a transition zone between the arid climate of North Africa and the temperate and rainy climate of central Europe, making it vulnerable to climate shifts caused by climate change (Lionello et al., 2012). Moreover, there is great consistency between models concerning the main characteristics of these projections over the region.

## Mean temperature and precipitation

Giorgi and Lionello (2008) reviewed climate change projections over the Mediterranean region based on a large ensemble of 17 global climate model (GCM) simulations, part of the ensemble of simulations analyzed in the fourth assessment report AR4 (IPCC, 2007). With respect to a median emission scenario (A1B), robust and large warming is projected at the end of this century (2071-2100) compared to the end of 20$^{th}$ century (1961-1990), with a maximum in the summer season. In summer (JJA) values would reach 3 °C to 4 °C over the sea, and 4 °C to 5 °C in inland areas, with maxima higher than 5 °C in the Sahara and Middle East. Substantial temperature increases will also occur in other seasons: +2 °C to 3 °C in winter and spring, and +3 to 4°C in fall. Changes would be about half a degree higher under the scenario with the highest emissions (A2 similar to the RCP8.5 scenario used in the AR5), and 1 °C less under the scenario with the lower emissions (B1). Climate change affects land areas more than the sea with differences between the Mediterranean Sea and the surrounding land regions of between 0.4 °C and 0.6 °C, reaching 0.9 °C in summer. The reduction in precipitation would be smallest in winter, where it would vary from no change in the northern Mediterranean to a 40% reduction in the south. In spring and fall, reductions in precipitation would vary between 10% and 40%. The average value of the large summer reduction would be in the range 25% to 30%, but some areas in the northeast and the south would undergo a reduction of more than 50%. In most model simulations, the reduction in mean annual precipitation, when averaged over the whole basin, is larger over sea than over land, except in winter. Like changes in temperature, changes in precipitation in the lower (higher) emission scenarios are smaller (larger) than in the median emission scenario. Both precipitation and temperature signals are projected to become progressively more severe during the course of the 21st century.

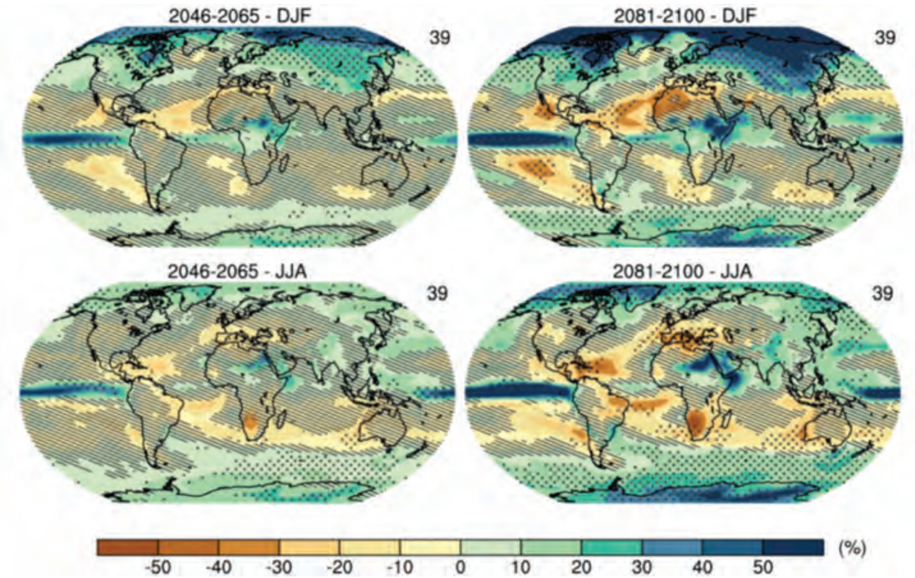


*Figure 1*
*Multi-model CMIP5 average percentage change in seasonal mean precipitation relative to the reference period 1985–2005 averaged over the periods 2045–2065 and 2081–2100 under the RCP8.5 forcing scenario. Hatching indicates regions where the multi-model mean is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model mean is greater than two standard deviations of internal variability and where 90% of models agree on the sign of change.*
*From fig. 12.22 WGI AR5, IPCC 2013*

The most recent results of emission scenarios of similar amplitude in IPCC AR5 are very similar. For instance, the maps presented in IPCC, 2013: Annex I, show that in the RCP8.5 comparable to the A2 emission scenario, warming over inland regions in about one century would be of the order of 3 °C to 5 °C in winter, and of 5 °C to 7 °C in summer. According to the same scenario, the decrease in precipitation over land during the October-March period would range from no change in the north to a 40% decrease in the south, and from 10% to 40% from north to south during the April-September period. However, according to the lower emission scenario (RCP2.6) that assumes the application of drastic mitigation climate policies, and has no corresponding scenario in AR4, the simulated changes would be much smaller. In this case, mean warming would not exceed 1.5 °C in winter and 2 °C in summer, even over the land areas. In addition, in this scenario, mean precipitation change would never exceed one standard deviation of internal climate variability.

These orders of magnitude are also consistent with the results of climate change scenarios run using regional climate models (RCMs). These models enable a better representation of the orography thanks to the improved resolution of the calculation, but they only cover a limited geographical area. Some results from an ensemble of simulations performed in the context of the ENSEMBLES European research project are reported in Planton et al. (2012). They consist in climate change projections over the Mediterranean region based on an ensemble of six regional climate change simulations with a resolution of about 25 km. Here we reproduce the simulated temperature and precipitation changes between 1961-1990 and 2071-2100.

In agreement with the GCM simulations, over land, the warming calculated by RCMs is roughly within the range of 2.5 °C to 3.5 °C in winter and 4 °C to 5 °C in summer (fig. 2). Warming over the sea is roughly in the range of 2 °C to 3.5 °C with less seasonal dependence. Precipitation changes simulated by RCMs (fig. 3) also generally agree with those simulated by GCMs with substantial future drying in all seasons and over all areas of the Mediterranean region, except in the northern part in winter.

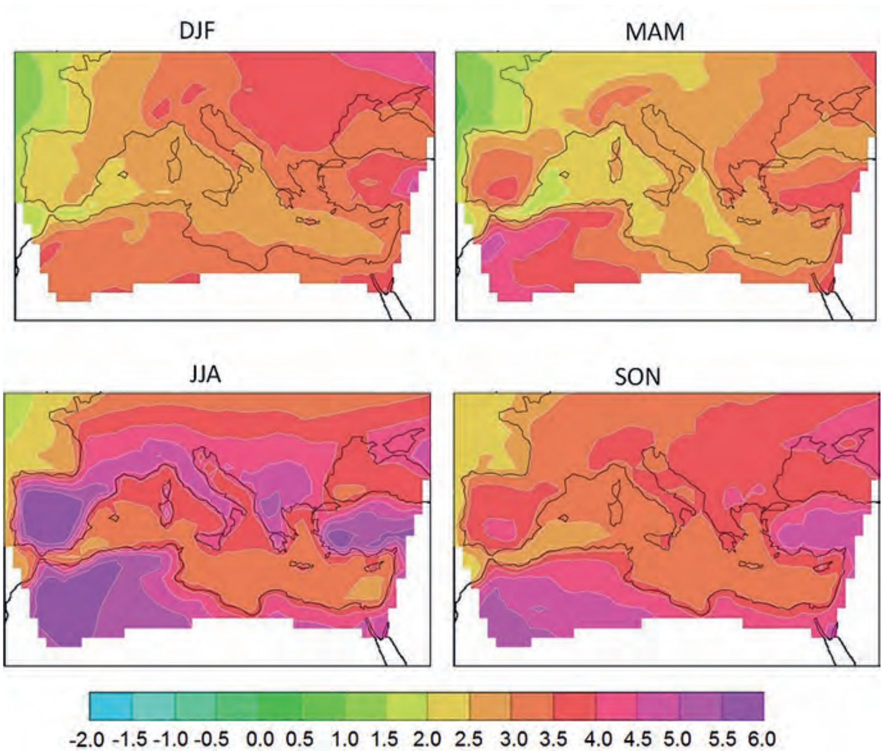


*Figure 2*
*Multi-model ENSEMBLES average percentage change in seasonal mean temperature relative to the reference period 1985–2005 averaged over the period 2071–2100 under the A1B forcing scenario.*
*From fig. 8.1 Planton et al. 2012.*

The main conclusion to be drawn from this synthesis of global and regional climate simulations is that in the Mediterranean at the end of the 21st century intense warming is almost certain and drying is very likely. The amplitude of these changes after 2050 depend to a great extent on the emission scenario concerned when the full range of the AR5 emission hypotheses is considered. However, actual values and the detailed spatial distribution of changes in precipitation, remain uncertain as they are strongly model dependent (Paeth et al. 2016).

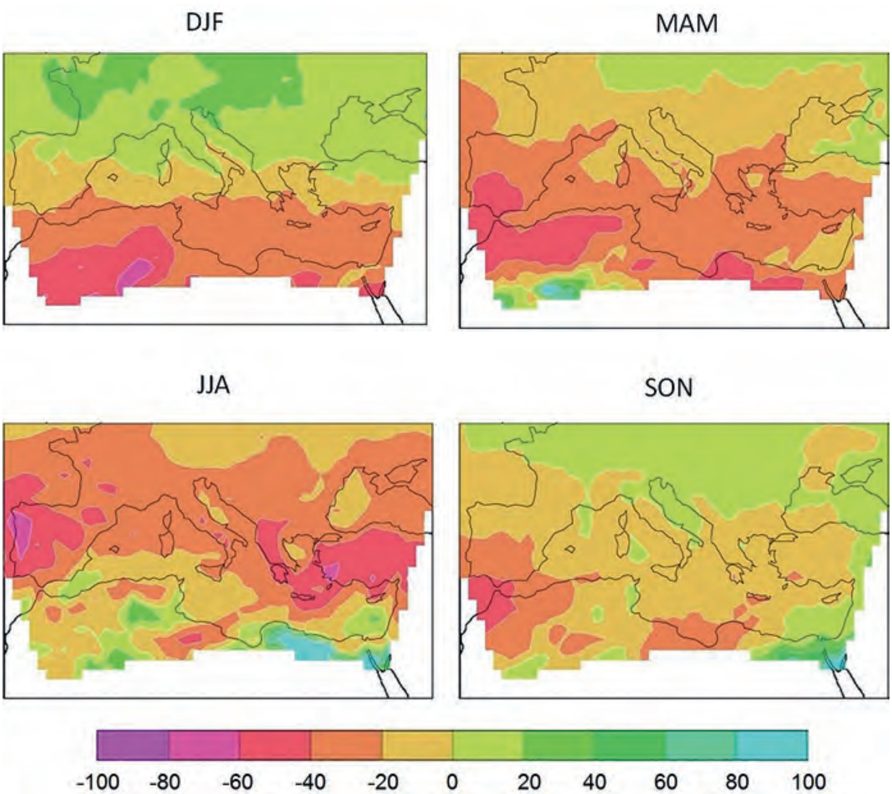


*Figure 3*
*Same as fig. 2 for precipitation.*
*From fig. 8.1 Planton et al. 2012.*



## Mean hydrological cycle

Mariotti et al. (2008) studied changes in the Mediterranean water cycle associated with the A1B emission scenario from GCM simulations synthesized in AR4. These authors showed that a simulated decrease in precipitation in the 20th century precipitation decrease would be followed by rapid drying from 2020 onwards (precipitation decrease is –0.02 mm/d per decade or –7.2 mm/y per decade). This amounts to roughly 15% less precipitation in 2070-2099 compared to 1950–2000, and an 8% decrease as early as 2020-2049. Since the multi model ensemble average has internal variability with reduced amplitude, actual variability would be larger than that depicted by the model ensemble mean. As precipitation is the main driver of the land surface hydrological cycle, other major hydrological indicators would also change similarly (see chapter 2.3). Concerning land surfaces, evapotranspiration would also decrease because of the drier soils, but, as increased surface temperature favors higher evaporation, the rate would be half that of precipitation. By 2070–2099, the projected difference between precipitation and evaporation decreases over land would be –0.09 mm/d (–0.01 mm/d per decade or -3.6 mm/y per decade). Some specific results concerning the future hydrological budget of the Mediterranean Sea are presented in sub-chapter 1.2.3.

The amplitude of the mean precipitation anomaly foreseen by 2020–2049 (about 0.1 mm/d or 36 mm/y) is comparable to that of the driest decadal spells experienced by the Mediterranean region in the 20th century. The Mediterranean region is indeed subject to climatic variability at a decadal time scale resulting partly from teleconnection with other regions (Ulbrich et al., 2012). Hence, at least in the short term (10–30 years), regional decadal anomalies and any potential for decadal predictability is likely to be critically dependent on the regional impacts of decadal modes of variability "internal" to the climate system.

## Warm spells

In addition to changes in mean values, climate projections also include significant changes in variability. Temperature and precipitation distributions would be subject to both a considerable shift and deformation, becoming broader in future climate scenarios. Increased interannual variability, especially in summer, along with the increase in mean warming, would lead to more frequent occurrence of extremely high temperature events. Like for precipitation, the decrease in mean precipitation and the increased frequency of large negative anomalies would increase the intensity and frequency of drought events (Giorgi and Coppola, 2009).

The detailed impacts of climate change on extremes linked to the water cycle (heavy precipitation, strong winds, drought events, flash floods) are described in chapter 1.3. We consequently focus here on warm spells or heat waves whose length, frequency, and/or intensity are judged to be *very likely* to increase throughout the whole region (IPCC, 2013).

The analysis of the RCM simulations in the context of the PRUDENCE and ENSEMBLES European projects revealed a general increase in temperature

### Box 1
### Future climate change in Morocco

Several socio-economic sectors (e.g. water resources and agriculture) are climate dependent in Morocco like in any many other Mediterranean countries. For example, dry years (e.g. 1980-1985 and 1990-1994) reduce crop yields and can negatively influence the GDP of the country. In the context of climate change, it is important to assess possible future changes in precipitation and temperature, two aspects of climate that directly influence agriculture, water resources and many other sectors.

Using the regional climate model ALADIN-Climat with a high resolution (12 km) over Morocco, we assessed future changes under two emission scenarios (RCP4.5 and RCP8.5). The main result obtained with the RCM is a quasi-general decrease in annual and winter rainfall amounts and an increase in temperature in all seasons, in both scenarios and at different time horizons.

Between 1971-2000 and 2036-2065, annual precipitation should decrease by 5% to 30% under RCP8.5 and the longest winter dry period should be extended by between 2 and 6 days from north to south. The number of high precipitation events is projected to decrease at both annual and winter scales whereas the amount of precipitation during this type of event should increase slightly, indicating fewer but more severe episodes. Warming is projected to concern all regions and mean temperature should increase by 1 °C to 1.6 °C from west to east under RCP4.5 and from 1.4°C to 2.2°C under RCP8.5. Warming should also manifest itself as more frequent summer heat wave days throughout the country (+1 to +4 days).

When future precipitation and temperature changes are combined, soil moisture is expected to be negatively impacted (see chapter 2.3). Taking into account the dependence of many vital sectors on climate and projected future changes, it is easy to deduce that adaptation is unavoidable to limit the negative impacts of climate change on the country to the greatest possible extent.

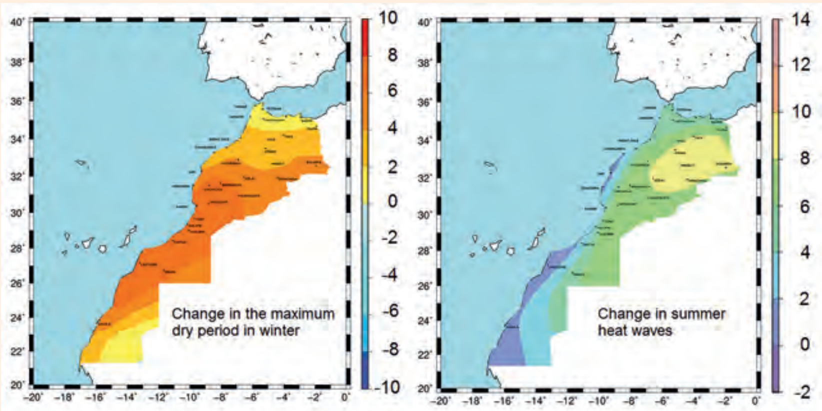


*Figure 4*
*Future changes in the maximum dry period in winter (in days) and in summer heat waves (in days) projected by ALADIN-Climat for Morocco under the RCP8.5 scenario between 2036-2065 and 1971-2000.*

extremes projected for the end of the 21st century in different emission scenarios (Planton et al. 2012). Using a statistical downscaling approach Hertig et al. (2010) also confirmed the trends in temperature extremes in the median A1B emission scenario. In general, the results indicate that changes in temperature extremes do not follow a simple shift of the whole temperature distribution to higher values but also due to a broadening of the frequency distributions of Mediterranean temperatures.

In more quantitative terms, Barriopedro et al. (2011) showed in particular that, according to the RCMs of the ENSEMBLES project, weekly heat spells of magnitude of the second week of August 2003 (7-day anomaly of 3.7 standard deviation of the 1979-1999 climatology), will probably occur in 2020–2049, with a best-guess return period of about 15 years in Western Europe, including the northern part of the western Mediterranean area. By the end of the 21st century, such extreme weekly heat spells are expected to occur about every 4 years, whereas some models show 2003-like anomalies about every second summer. In a study of projected heat extremes over the eastern Mediterranean and the Middle East (EMME) with a specific RCM, Lelieveld et al. (2014) projected that by the end of this century, in most cities, the coolest summers may be warmer than the hottest ones of the 1961-1990 period, according to all the scenarios considered (B2, A1B and A2).

Projections of extreme temperature changes always show regional variability that can be partly attributed to mechanisms involving coupling between the surface and the atmosphere. For instance, a study by Zittis et al. (2014) also covering the EMME region, showed that heat waves might be intensified by a decrease in soil moisture due to reduced cooling caused by evaporation. This mechanism has been shown to play a role in particular in Italy, the Balkans and Turkey, but this result remains to some extent model dependent.



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Sub-chapter 1.2.3

# The Mediterranean Sea in the future climate projections

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## Introduction

As a semi-enclosed and highly evaporative basin, the Mediterranean Sea has a specific thermohaline circulation characterized by deep convection in certain zones (Gulf of Lion, the Adriatic, Levantine and Aegean Seas). The contrast between the fresher (hence lighter) waters west of the Strait of Gibraltar compared to the saltier (hence heavier) Mediterranean waters east of it, is the principal forcing of the outflowing water vein and the compensating inflow of light Atlantic waters floating as a surface layer. The entire thermohaline circulation has a time scale of 75 to 100 years. How the circulation of the Mediterranean Sea will evolve under a changed climate is a major issue. Other key questions concern changes in the surface characteristics: sea surface temperature and salinity (SST, SSS), surface currents, sea level and waves. An overview of the projected future state of the Mediterranean Sea and associated uncertainties are presented in the following.

# Models and methods

The assessment of the effects of climate change on the Mediterranean Sea over the 1950-2100 period and under several socio-economic scenarios is based on different types of model projections from (i) general circulation models (GCM) used in the coordinated Coupled Model Intercomparison Projects (CMIP), (ii) higher resolution regional climate models (RCM) dedicated to the study of the Mediterranean region and/or Mediterranean Sea. RCMs including (1) atmosphere-only regional climate models (ARCM) from international coordinated programs (CORDEX) and European projects (e.g. PRUDENCE, ENSEMBLES) are used to assess changes in the atmosphere above the sea; (2) forced *regional ocean models* are used to assess impacts on the sea itself; and (3) fully coupled atmosphere-ocean regional climate models (AORCM), also called regional climate system models (RCSM), take into account the high resolution and high frequency coupling between the various components of the regional climate system. The use of RCSM for future projections started quite recently (Somot et al. 2008, Carillo et al. 2012) before being coordinated in the European project CIRCE (Dubois et al. 2012; Gualdi et al. 2013) and currently in the Med-CORDEX initiative (Ruti et al. 2016, see Box 1). CMIP5-based and CORDEX-based analyses are still ongoing and more results are expected in the coming years.

The various modeling approaches used up to now should be considered as complementary as they all have their advantages and drawbacks and none has been demonstrated to be better than the others in assessing the effect of climate change on the Mediterranean Sea.

**Box 1**
**Med-CORDEX**

The aim of the Coordinated Regional Downscaling Experiment (CORDEX), of the World Climate Research Program (WCRP), is to provide a coordinated framework to evaluate and improve regional climate modelling and to produce fine scale climate projections for identified regions worldwide.

The specific climate, topographical and anthropogenic factors that characterize the Mediterranean region make it a good candidate for regional climate modelling and the region was indeed chosen as a CORDEX sub-domain leading to the Med-CORDEX initiative (www.medcordex.eu) endorsed by Med-CLIVAR and HyMeX. The Med-CORDEX initiative is a voluntary-based approach and was proposed by the Mediterranean climate research community as a continuation of previous initiatives. It takes advantage of new very high resolution regional climate models (RCMs, up to 10 km) and of new fully coupled regional climate system models (RCSMs), coupling the various components of the regional climate. Med-CORDEX is a unique framework in which the research community will make use of these new modelling tools to increase the reliability of past and future regional climate information and to better understand the processes responsible for the Mediterranean climate variability and trends.

It is worth mentioning here that empirical downscaling approaches, very common over land, are only rarely used over the sea (Maciàs et al. 2013) probably due to the lack of in-situ data to train the statistical methods.



# Future evolution of the Mediterranean Sea forcings

As mentioned in the previous sub-chapter, there is a wide consensus that the future Mediterranean climate will be characterized by drier and warmer conditions. In line with these changes, the components of the Mediterranean Sea surface freshwater budget, evaporation, precipitation, rivers and Black Sea freshwater inputs, will also change (Mariotti et al. 2008, 2015, Sanchez-Gomez et al. 2009, Elguindi et al. 2011, Dubois et al. 2012, Planton et al. 2012, Adloff et al. 2015). Between the end of the 20$^{th}$ century and the end of the 21$^{st}$ century, most studies predict a decrease in precipitation of between -5% and -15% over the basin, although some studies project a reduction of up to 28%. On the other hand, evaporation tends to increase, with some models projecting an increase of up to 18%. River runoff and Black Sea water net inflow are both projected to decrease respectively by down to -87 % and -102 %. The latter value implies that, according to some future projections, the Black Sea will become an evaporative basin and as a consequence, the net water flow through the Dardanelles Strait would reverse (from the Mediterranean to the Black Sea). Changes in the components of the water budget depend to a great extent on the socio-economic scenario chosen (Adloff et al. (2015): the higher the GHG emissions, the greater the response of the water flux. However, changes in the Mediterranean Sea water budget are not expected to emerge from natural variability before the middle of the 21$^{st}$ century. It is worth noting that the future change in the Nile River discharge is a challenging issue due to the considerable influence of the management of this river, which has not been correctly tackled up to now (see Somot et al. 2006 and Dubois et al. 2012 for a discussion of this issue).

Future changes in the components of the Mediterranean Sea surface heat budget: shortwave and longwave radiation, latent and sensible heat fluxes, have been less frequently studied (Somot et al. 2006, 2008, Dubois et al. 2012, Gualdi et al. 2013, Adloff et al. 2015). These studies show that in all available climate projections, the surface heat loss from the Mediterranean will decrease. The projected change in surface heat change ranges from +25 % to +118 %, meaning some models predict that the Mediterranean Sea could even gain heat through the surface in the future. The changes in surface heat fluxes are tightly correlated with the GHG concentrations in the scenarios.

Few studies have assessed changes in the speed and direction of the wind over the Mediterranean Sea (Somot et al. 2006, Dubois et al. 2012, A. Dell'Aquila CLIM-RUN project, unpublished). From these RCM-based studies, changes are not expected before the middle of the 21st century but a decrease in wind speed is projected for the end of the 21st century. The only sub-basin where an increase in wind speed is expected is the Aegean Sea (Somot et al. 2006).

Concerning the heat and salt transport from the near-Atlantic Ocean into the Mediterranean Sea, the global temperature increase will certainly lead to an increase in the temperatures of the incoming waters through the Strait of Gibraltar. This, together with the change in the surface heat budget, would increase the heat content of the Mediterranean Sea. In addition, an increase in water lost through the sea surface would increase the net water transport at the Strait and probably increase salinization of the basin, since more salty water will enter the basin to compensate for the increase in the fresh water deficit. However, the expected change in salinity in the near Atlantic Ocean is very uncertain in GCMs (Marcos and Tsimplis 2008, Carillo et al. 2012). Some global models project an increase in salinity in the northeast, whereas other models suggest freshening. In the latter case, the waters entering the Mediterranean through the Strait of Gibraltar could be fresher and could at least partially compensate for the effects of increased water transport. The evolution of salinity forcing coming from the Atlantic Ocean is today probably one of the main uncertainties of future projections concerning the Mediterranean Sea.

# Future evolution of sea circulation, temperature and salinity

## Sea surface temperature and salinity

In the climate change scenarios, GCMs and RCMs clearly predict warming of the Mediterranean Sea surface, with a significant, nearly homogenous increase of up to 1.5 °C – 3.1 °C in the annual mean SST for the end of 21st century compared to the present (e.g. Somot et al. 2006, Adloff et al. 2015). The warming rate depends at the first order on both the time horizon and the greenhouse gas emission scenario (Shaltout et al. 2014, Adloff et al. 2015, Mariotti et al. 2015). However, warming will always remain below than that of the air due to ocean thermal inertia. Some studies indicate greater warming in summer compared to winter. Even if there is still no clear consensus on the spatial variability of the increase in SST, Adloff et al. (2015) identified the Balearic Islands, the northwest Ionian, the Aegean and Levantine Seas as the regions with maximum warming.

The future evolution of sea surface salinity (SSS) is less certain as it depends on two competing and opposite forcings (see above). This leads to non-homogeneous, geographically and seasonally dependent projected changes for SSS. A progressively higher SSS is however generally projected with values ranging from 0.06 psu to 1 psu over the next 100 years. Changes in SSS often remain undetectable until the middle of the 21st century and more pronounced salinization is identified in the Aegean and the Adriatic, possibly driven by a marked decrease in Black Sea and Po river runoff (Planton et al 2012, Adloff et al. 2015, see Figure 1).

Changes in SST and SSS have opposite effects on the density of the surface waters. Pessimistic scenarios project a decrease in surface density (due to the marked increase in temperature) whereas some optimistic scenarios project an increase in density (related to a moderate increase in temperature and sometimes major changes in SSS in the near Atlantic Ocean).

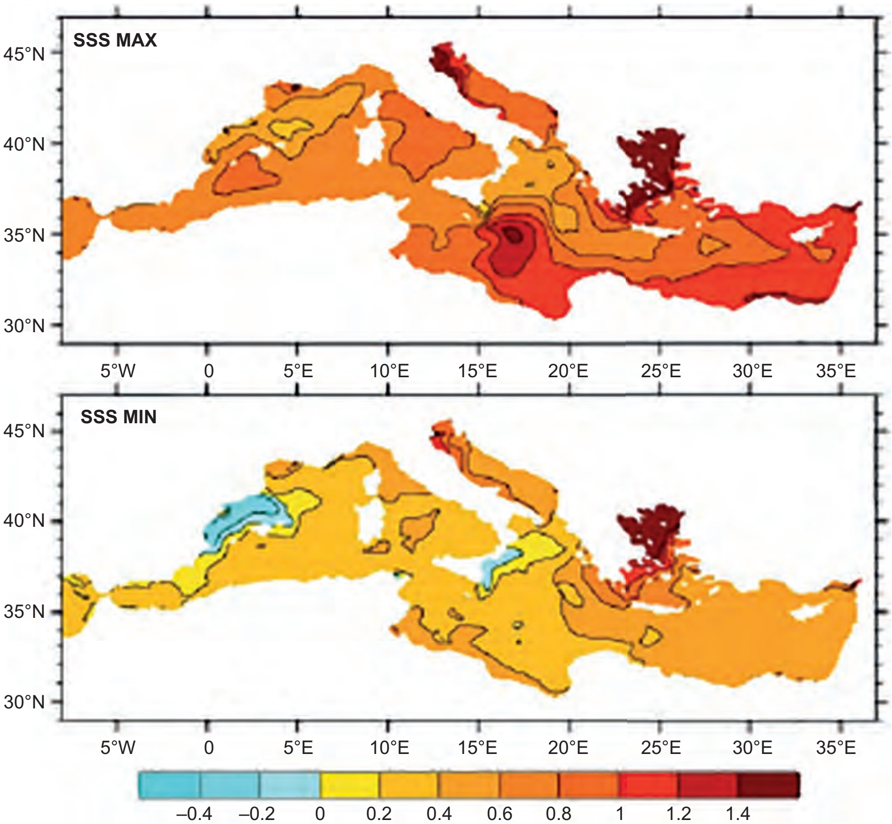


*Figure 1*
*Spatial composite of the expected minimum and maximum changes in SSS at the end of the 21st century compared with the end of the 20th century based on a 6-member ensemble covering various sources of uncertainty (adapted from Adloff et al. 2015)*

## Deep layer characteristics

The surface climate change signal is propagated efficiently towards the deeper layers through the Mediterranean thermohaline circulation and more particularly through deep convection and dense water formation processes. This leads to relatively strong signals in the deep layers of the Mediterranean Sea with a mean warming of about +0.4 °C in total heat content in the middle of the 21st century (Carillo et al. 2012) and between +0.9 °C and +2.5 °C at the end of the 21st century mostly depending on the socio-economic scenario concerned but also on the choice of the model and on the modeling strategy applied (Somot et al. 2006, Marcos and Tsimplis 2008, Adloff et al. 2015, Maciàs et al. 2016). For the total salt content of the seawater, no significant signal is projected for the middle of the 21st century (Carillo et al. 2012) while values ranging from +0.2 psu to +0.9 psu, (Somot et al. 2006, Adloff et al. 2015, Maciàs et al. 2016) are projected for the end of the 21st century mostly due to the uncertainty related to the changes in the near Atlantic characteristics, in river discharges, and in the strength of the thermohaline circulation under the current climate. This means the socio-economic scenario is not the main source of uncertainty in future changes in salinity.

## Sea circulation

Although sea surface circulation is difficult to assess from the published literature (only one study), it is projected to undergo some modifications with a northward shift of the eastward moving surface water veins in both the western and eastern basins. For example in Figure 1, the areas with a decrease in salinity in the Balearic area and in the northern Ionian Sea are signatures of these changes in surface circulation (Adloff et al. 2015).

All published studies agree on a weakening of the open-sea deep convection, the winter deep water formation and the related branch of the thermohaline circulation for the western Mediterranean Sea (Thorpe and Bigg 2000, Somot et al. 2006, Adloff et al. 2015), which, in some studies, is projected to be very strong and to occur very early in the 21st century (Somot et al. 2006). The picture in the eastern Mediterranean Sea is more contrasted with weakening in some simulations (Somot et al. 2006) but enhanced convection and thermohaline circulation in others and even some situations where the Aegean Sea becomes the first source of Eastern Mediterranean Deep Water (EMDW) such as during the Eastern Mediterranean Transient (EMT) in the 1990s (Adloff et al. 2015). This EMT-like situation is attributed to stronger winds over this area and to a drastic reduction in the flow of freshwater from the Black Sea into the Aegean Sea. The results concerning future changes in the Mediterranean thermohaline circulation should to be interpreted with caution as the models still have difficulty representing the current climate thermohaline circulation.

# Water transport through the Strait of Gibraltar and Mediterranean outflow water

Changes in the Mediterranean thermohaline circulation are intimately connected to the exchange of water and heat with the Atlantic Ocean through the Strait of Gibraltar. Adloff et al. (2015), project an increase of 0.02 Sv (relative to the actual value, 0.05 Sv) in the net water flux at the Strait of Gibraltar to compensate for the increase in net water loss from the sea surface. The net heat and salt transport are projected to increase by +2 $Wm^{-2}$ and +11 $10^5$ $kg.s^{-1}$, respectively. The Atlantic Ocean is therefore projected to increase its supply of mass, salt, and heat to the Mediterranean Sea. Concerning the two-way exchange, a decrease in outflow (~-0.02 Sv) and a slight change in inflow (an increase of less than +0.01) are projected. These changes reflect changes in the hydrographic characteristics of the Mediterranean Sea but also probably in those of the eastern Atlantic Ocean. However the projected changes vary among models, with some models showing a reduction in the net heat gain and in the salt loss at the Strait of Gibraltar (Somot et al. 2006). The model simulations underline the complexity of the expected changes in water transport through the Strait of Gibraltar as they are the result of competing changes in temperature and salinity.

# Mean sea level, storm surge and wind waves

## Mean sea level

Modeling mean sea level variability in the Mediterranean Sea is not straightforward. On one hand, GCMs do not have enough spatial resolution to reproduce the main mechanisms that control regional dynamics. For instance, the redistribution of heat inside the basin is strongly biased if the resolution is too coarse. This has a major impact on the reliability of temperature projections in the Mediterranean, and consequently on thermal expansion. On the other hand, at low frequencies, the variability of Mediterranean sea level is strongly influenced by changes in the nearby Atlantic, which are usually not included in regional climate models (RCMs) thus making it impossible for them to estimate long term trends of total sea level.

Up to now, studies on the projections of sea level in the Mediterranean have focused on one of the components of sea level variability, the steric component (i.e. linked to changes in the density of the water column). This is only a part of the story as long as the projected sea level changes in the nearby Atlantic (i.e. either due to land ice melting or to changes in the circulation) are not taken into account. Moreover, Jordà and Gomis (2013) showed that ignoring changes in the amount of salt and using only the steric component to characterize the total sea level can lead to false conclusions in the Mediterranean. In particular, the steric component is equal to total sea level only in those cases where the mass in the water column is preserved. However, major changes in salt content are expected in the Mediterranean Sea that would not only increase the density of the water column but also change the mass. In other words, an increase in salinity in the basin would not imply a contraction of the water column, even if the steric component were negative. Therefore, projections based only on the steric component should be interpreted with caution.

Using the simulated evolution of the steric component in the Mediterranean, Carillo et al. (2012) found a thermal expansion of about 5 cm in 2050 under the A1b scenario. It can also be concluded from their study that differences in the temperature of the waters flowing into the Mediterranean from the Atlantic will have little effect on the thermal evolution of the basin. Gualdi et al., (2013) found an increase in the steric component of about 15 cm in 2050 under the A1b scenario, although it should be noted that this is not completely representative of total sea level as the salinity effects were not filtered out. Adloff et al. (2015) projected a basin average thermal expansion ranging from +34 to +49 cm at the end of the 21st century under scenario A2. These authors found that the discrepancies are mainly due to the conditions prescribed for the Atlantic forcing, thus somewhat in disagreement with Carillo et al. (2012), who found no significant sensitivity to Atlantic forcing.

In addition to the local thermal expansion, other components will play a role in future changes in sea level in the Mediterranean. In particular, melting of terrestrial ice due to global warming will be converted into a quasi-homogeneous global signal. This could mean an additional rise of between 10 and 60 cm in the level of the Mediterranean Sea (Spada et al. 2013). Changes in the northeast Atlantic circulation will also represent an additional 10-30 cm (Bouttes et al. 2012). In summary, the projected rise in the average sea level of the Mediterranean basin is estimated to be between 40 cm and 110 cm at the end of the 21st century with respect to the present climate. The range reflects the uncertainties linked to the GHG emissions scenario and to uncertainties in the modelling system. Finally, it is worth mentioning that changes in circulation within the Mediterranean can also sustain local changes that differ from the basin average Figure 1. These changes can be up to ± 10 cm (Figure 2) although different models differ in the patterns of change and there are no dedicated studies addressing the robustness of these regional patterns.

## Storm surge

Concerning the extreme sea level events, studies show that projections of extreme sea level events in the Mediterranean are very sensitive to the choice of atmospheric forcing. Marcos et al. (2011) point to a reduction in the average number of positive surges, whereas negative surges will increase throughout the 21st century. Conte and Lionello (2013) found an overall decrease of ~-5% in the magnitude in positive surges with changes up to ~-10% in some locations along the Mediterranean coasts. However, these authors reported marked differences among simulations, and that the results were not spatially coherent.

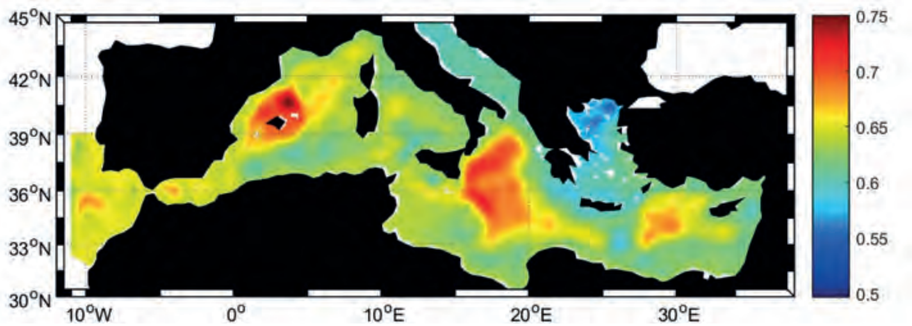


*Figure 2*
*Projection of sea level change for the period 2080-2100 with respect to the period 1980-2000. The result is the combination of outputs of an ensemble of regional climate models combined with the CMIP5 projections for the Atlantic changes all run under moderate GHG emission scenarios (A1b and RCP6.0).*

## Wind waves

Future changes in waves will be determined by future changes in the wind field over the Mediterranean Sea. Lionello et al. (2008) ran a regional wave model of the whole Mediterranean Sea under scenarios A2 and B2. These authors found that the mean significant wave height field over a large fraction of the Mediterranean Sea would be lower all year round at the end of the 21st century with a greater reduction (about -20 cm) in winter under scenario A2. The changes are similar, though smaller and less significant, under the B2 scenario, except during winter in the north-western Mediterranean Sea, where the mean significant wave height is projected to be higher than at present. Concerning extreme events, these authors also found smaller values in future scenarios than in the present climate. They also showed that, in general, changes in significant wave height, wind speed and atmospheric circulation were consistent.

Based on statistical downscaling, Pérez et al. (2016) also found a decrease in significant wave height of -5 cm under scenario RCP8.5, of -3 cm under scenario RCP4.5, and no change under scenario RCP 2.6. These results are in agreement with the above mentioned work and point to a larger decrease in wave height under higher emission scenarios.

# Conclusions

Several robust and significant conclusions can be drawn such as general warming and an increase in the salinity of Mediterranean waters, as well as the sea level rise due to the propagation of the global signal. However the changes in temperature and salinity have opposite and competing effects on the change in water density and hence on changes in vertical stratification, in the Mediterranean thermohaline circulation, and in the total steric sea level. Whereas some scenarios project a weakening of the thermohaline circulation especially in the western Mediterranean basin, others predict that the Mediterranean Sea could enter an EMT-like state. As a consequence, future changes in water and heat exchanges at the Strait of Gibraltar, being part of the thermohaline circulation, are less certain but will very likely be an increasing source of heat and salt for the deep layers of the North Atlantic Ocean during the course of the 21st century. Similarly, the uncertainty on the expected sea level rise is as high as that for oceans worldwide.

Changes related to the water cycle are not expected to emerge from the natural variability before the middle of the 21st century, whereas changes related to the heat cycle are already being observed. Concerning the end of the 21st century, as expected, the choice of the socio-economic scenario is often the most important source of uncertainty, but future changes in conditions in the Near Atlantic Ocean may outweigh salinity related changes including the Mediterranean thermohaline circulation. Future changes in river discharges could be the main source of uncertainty in some key sub-basins.

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Chapter 3

# Hydro-meteorological extremes

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## Abstract

The Mediterranean region concentrates all the main natural risks linked with the water cycle, including heavy rainfall leading to flash floods, strong winds and associated large swells and storm surges, heat waves and droughts accompanied by forest fires. The magnitude and frequency of these hydro-meteorological extremes could be significantly affected by the ongoing climate change. The study of extremes is based on the combination of observations, data analysis and numerical modeling to extrapolate the observations and produce possible future trends. However, studying extremes is a complex task for several reasons. Extremes are, by definition, rare events and the existing datasets against which scientific theories and models can be calibrated and tested are only progressively enriched. Extreme events are often characterized by large spatial and temporal variability that is hardly captured by existing observation networks. Moreover, measurements of exceptional values may also be affected by significant uncertainties. This explains our still partial knowledge and the sometimes contradictory conclusions of scientific studies on past observed and future trends, for instance. Our knowledge of hydro-meteorological extremes has nevertheless advanced substantially in recent years thanks to the development of databases and dedicated research programs. This chapter presents a state of the art review of extremes around the Mediterranean, their seasonal and geographical patterns, and their observed and projected trends. Remaining questions and uncertainties are also discussed.

## Résumé

Les régions méditerranéennes sont particulièrement soumises aux risques hydro-météorologiques, comme les pluies intenses et les crues rapides, les tempêtes induisant des submersions marines et des fortes houles, les vagues de chaleur et les sécheresses favorisant les feux de forêts. L'intensité et la fréquence de ces événements hydro-météorologiques extrêmes sont susceptibles d'évoluer sous l'effet du changement climatique. L'analyse de ces événements extrêmes repose sur l'observation, l'analyse de données et la modélisation numérique afin d'interpréter et d'extrapoler les observations et de prévoir les évolutions à venir. L'étude des extrêmes est cependant une tâche particulièrement complexe. Les événements extrêmes sont rares par nature. Les bases de données disponibles ne s'enrichissent donc que très progressivement. Ces événements sont par ailleurs souvent caractérisés par de fortes hétérogénéités spatiales et temporelles que les réseaux de mesure existants peuvent difficilement capturer précisément. La mesure de valeurs exceptionnellement élevées, pour lesquelles les réseaux de mesure n'ont pas été conçus et ajustés, peut aussi être entachée d'incertitudes importantes. Tout ceci explique notre niveau de connaissance encore aujourd'hui imparfait et les conclusions parfois contradictoires des études scientifiques sur les évolutions passées et futures. Nos connaissances ont cependant fortement progressé ces dernières années grâce à un certain nombre de programmes de recherche dédiés et à la mise en place de bases de données partagées. Ce chapitre présente l'état des connaissances sur les phénomènes extrêmes hydro-climatiques autour de la Méditerranée, leur répartition géographique et saisonnière, leurs évolutions passées et à venir. Les questions non résolues et les incertitudes sont aussi exposées et discutées.

Sub-chapter 1.3.1

# Heavy precipitation in the Mediterranean basin

## Observed trends, future projections

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This sub-chapter focuses on extreme rainfall around the Mediterranean basin. It provides an overview of the state-of-the-art knowledge of past and expected future changes.

The high vulnerability of the Mediterranean area to future anthropogenic climate change has been pointed out since the early 2000s (Giorgi 2006) based on the consistency of the climate projections made by many atmosphere-ocean general circulation models (AOGCM) in the successive phases of the Coupled Model Intercomparison Projects (CMIP).

Whatever the model types, climate projections are resolved at scales of a few kilometers to hundreds of kilometers. The question of how humans will perceive these projections at the scale of an urban area or a small catchment basin is still open. Behind this is the question of the scaling of rainfall with horizontal resolution and of the processes involved when a physical risk becomes a human hazard. We tackle these questions in part by examining how changes in extreme rainfall in the recent past scale between regional and local diagnostics in the following section. In the second section, we review the main results of regional climate simulations of extreme rainfall.



# Extreme precipitation trends in the recent past

## Methods for trend analysis of extreme rainfall

Trends in extreme rainfall reported in the literature are examined using a variety of methodologies to which the results are sensitive.

Two main approaches exist. The first is based on climate indices. Most indices describe the occurrence and the intensity of moderate extremes that typically occur several times a year. The Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDI) recommends the use of 11 indices related to precipitation. This broad spectrum of indices is used to cope implicitly with the variety of rainfall. The relevance of the indices can be discussed when comparing their use from a region to another and their partial assessment of the extreme rainfall phenomenon.

The second set of approaches focuses on the heaviest rainfall fully characterizing them by modeling their probability density function in the framework of the "Extreme value theory" (Coles, 2001). These approaches have the advantage of being scale independent. Thus the same theoretical framework can be used to analyze precipitation at different scales (rain gauges, climate model fields, etc.). Moreover fitting a probability density function onto the data implicitly mixes the intrinsic information of the dataset and the theoretical knowledge behind the statistical model. This leads to implicit filtering of sampling issues in rainfall data. However such an approach is seldom used in the literature.

Most studies assess changes in extreme precipitation by regressing climate indices with time or in the case of the statistical model approach, by capturing the temporal evolution of one or more parameters of the statistical model.

Another approach is to consider, rather than time, state parameters of the atmosphere (temperature, humidity) or a large scale diagnosis of atmospheric circulation (North Atlantic oscillation, NAO) as covariates either in the climate index regressions or in the statistical model parameters. This framework is useful to compare past and future climates, however it does not really provide a quantitative assessment of the rate of change.

## From regional to local trends in the recent past

Casanueva et al. (2014) provided a regional picture of the trend in extreme rainfall on the western side of the Mediterranean basin by analyzing changes in the relative contribution of daily rainfall above the 95$^{th}$ percentile to the total amount of rain (R95pTOT) for the period 1950-2010. Their study was based on the E-OBS data (high-resolution gridded data set of daily climate over Europe) at a resolution of 0.5°. At this spatial resolution, the trend is either significantly positive at specific points or null for most of the areas, but seldom negative. Significant positive trends are in the range of 1.5% to 4% per decade, which corresponds to changes in the range of 8% to 25% from the 1950s to the present.

Over North Africa, R95pTOT shows almost no trend except at the extreme east of the Atlas Massif, the north of the Algerian-Tunisian border where it tends to increase by about 4% per decade. None of the local studies in this region (Tramblay et al. (2012a); Donat et al. (2014) and Taibi et al. (2015)) corroborates the increase in heavy rainfall at the large scale of 0.5° reported in Casanueva et al. (2014) nor reveals any consensus in this area.

In the north-western part of the Mediterranean basin, the positive trends of R95pTOT at 0.5° resolution are reported over the main mountain massifs from the eastern Pyrenees in Spain to the Alps and Balkans around the Adriatic and Black Sea. In these regions, at some local spots, the extreme rainfall shows a positive trend of around 40% for the 90$^{th}$ percentile of daily rainfall, but the results depend on the area studied and on how extreme rainfall is defined. This is particularly apparent over the Iberian Peninsula, where contrasting rainfall regimes are observed from the ocean shore to inland Spain.

Kostopoulou and Jones (2005) collected rain gauge data from 10 countries around the Mediterranean from Italy to Israel and computed the ETCCDI indices characterizing extreme rainfall. The dataset spans the period from 1958 to 2000. In the western part of the basin, they obtained similar results to those described above, but their results in the eastern part differed, although they were in agreement with those of other local studies. The quasi-homogeneously positive trend in extreme rainfall in Italy, can become significantly negative moving eastwards toward the Balkans, Peloponnese, Turkey and Cyprus. In Israel, these trends vary from significantly negative to significantly positive passing through zero among sites located only a few tens of kilometers apart.

Again it appears that designing a robust method to study extreme rainfall is still a scientific challenge (see Box 1.)



# Regional change in extreme rainfall in future climates

## Modeling background

Most models predict a reduction in annual precipitation, associated with a larger increase in temperature than in the surrounding regions, except in snow covered areas that are subject to strong winter warming due to snow-albedo feedback.

## Box 1
## Trends in extreme rainfall in southern France

The Mediterranean region of southern France is prone to heavy rainfall that can have major impacts on humans and society in general. In the framework of the HyMeX program, a sensitive study was conducted on how the definition of extreme rainfall influences the resulting extreme rainfall trends. Different methods are being applied independently by three French labs (HSM-Montpellier, CNRM and LTHE Grenoble) on the same dataset. The first result is that the statistical extreme value theory is the most efficient framework in the context of extreme rainfall and its possible evolution.

Figure 1 shows the relative trend in the annual maxima of daily rainfall computed from both rain gauges and spatialized rainfall data from 1958 to the present. Extreme rainfall in the study region was most likely stationary from 1958 to 1985. From 1985 on, we hypothesize a linear evolution in the statistical distribution of extreme rainfall. The figure below shows that the trend is spatially highly variable over the region and sometimes even at neighboring rain gauges such as over the mountain range delineated by the location of the main mountain peaks (triangles). There is a wide region in the center of the map extending from the Cévennes mountain range to the Alps passing though the Rhône river valley, in which both local and spatially extreme rainfall have increased by 20% to 60% in 30 years.

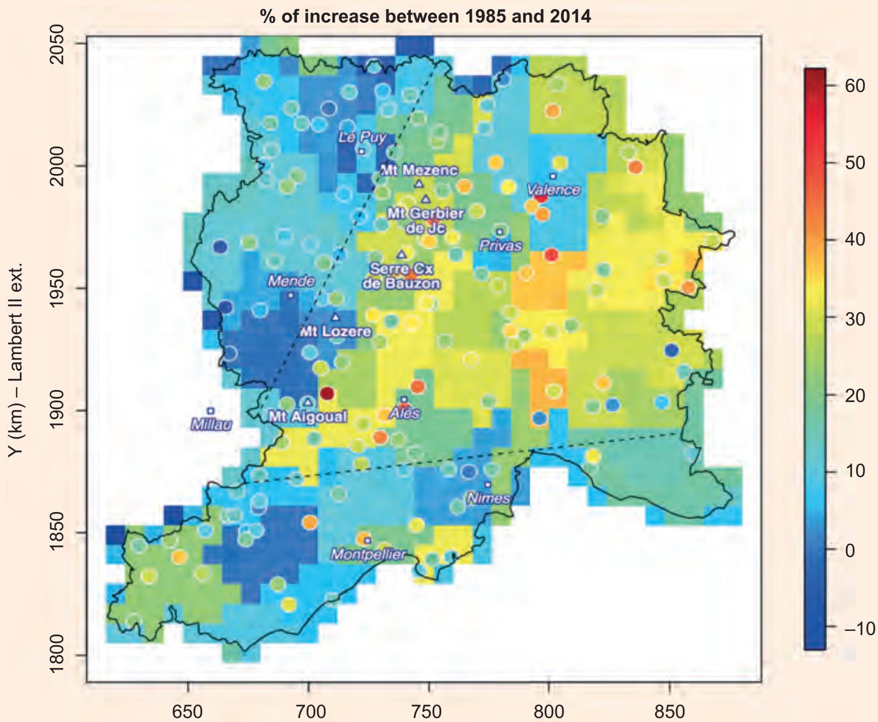


*Figure 1*

*Increase (in %) in the annual maxima of daily rainfall during the period 1985-2014 relative to the average of the series of annual maxima of daily rainfall for each rain gauge (colored dots) and of the spatial data (colored 8x8 km2 squares). Adapted from Blanchet et al. (2016).*

However, the complexity of both the topography and the land/sea distribution of the Mediterranean area makes it impossible for either the atmospheric or the ocean models used in the Coupled Model Intercomparison Project (CMIP) to faithfully represent the Mediterranean features. For example, atmospheric models with a horizontal resolution of more than 100 km cannot perfectly represent the Massif Central and the Rhône valley and are consequently unable to reproduce the northerly Mistral winds over the Rhône valley.

For these reasons, a concerted strategy of climate simulations at higher resolution has been implemented in the Mediterranean basin. In the PRUDENCE project (Christensen et al. 2007) a first approach was attempted with 50 km resolution regional climate models over Europe (RCMs), driven by observed sea surface temperature (SST) in the present climate or with SST plus the local SST response by Hadley Centre Coupled Model. The results confirmed and even amplified the risk of drought over southern Europe. Unfortunately several RCMs did not cover the southern part of the Mediterranean basin. Another limitation of the project was the use of a single greenhouse gas (GHG) scenario (SRES-A2) and a single SST scenario (HadCM). In the following European project, ENSEMBLES (van der Linden, 2009), the horizontal resolution was increased to 25 km, the whole Mediterranean basin was taken into account in the RCM domains, and several SST scenarios were used (most including the bias of the coupled GCM). The GHG scenario was SRES-A1B, considered to be more credible than SRES-A2. ENSEMBLES results confirmed the consistent response over the Mediterranean area, and added a probability layer, with the use of weights for the different GCMs (Christensen et al. 2010)

The CORDEX project (Giorgi et al. 2009) was an extension of the former PRUDENCE, ENSEMBLES, and other extra-European projects to all continents of the world. The common denominator is a minimum horizontal resolution of 50 km and the use of two GHG scenarios (RCP45 and RCP85). Two sub-projects concern the Mediterranean area: EURO-CORDEX (Jacob et al. 2010) covers a larger domain (from Iceland to the Red Sea) with a higher resolution (12 km). MED-CORDEX (Ruti et al. 2016) kept the original 50 km resolution, but included a regional model for the Mediterranean Sea, rather than prescribing SST from CMIP5. CORDEX is not only a scenario experiment, but includes validation with the RCM driven by ERA-interim reanalyses. CORDEX is still an on-going project. Despite the abundant literature on the validation phase, still no synthesis papers have been published specifically concerning extreme precipitation scenarios over the Mediterranean basin.

## Regional climate change: response to +2 °C

The most recent attempt to synthesize the climate response of a large number of RCMs over the Mediterranean basin (and more generally over Europe) was the IMPACT2C European project. This project relied on high resolution (12 km) contributions to EURO-CORDEX. The originality of the approach, compared with FP5-PRUDENCE or FP6-ENSEMBLES, is the choice of the time period to define the future climate. Rather than a fixed 30-year period like 2021-2050 or 2071-

2100, in which all models use the same GHG concentration (for a given scenario), each RCM uses a 30-year period for which the mean global temperature in the driving GCM is 2 °C above the pre-industrial level. As the reference period to evaluate the climate change at regional scale is 1971-2000, this means a global temperature increase of 1.54 °C with respect to this reference.

With this new approach, the model spread is reduced, at least as far as temperature is concerned: by construction the spread of the global temperature responses is zero. The GCMs with high climate sensitivity to GHG impose an early period for the "future climate" in the RCMs they control. For example, in the RCP8.5 scenario, the center of such a period among the CMIP5 GCMs spans 2020 to 2060. Mean precipitation (not shown) tends to decrease in any season, but the decrease is generally modest (less than 5%). Heavy precipitation can be measured by the 95$^{th}$ percentile of the amount of precipitation on rainy days (defined as days with precipitation of more than 1 mm). This parameter is maximum in the fall (up to 35 mm/day in some areas). More than 80% of the models agree on the sign of the response over the major part of the domain, which is a good consensus. Figure 2 shows the mean model response for the change in the 95$^{th}$ percentile of daily precipitation in summer and fall. Some areas of France show a negative response (less heavy precipitation) in summer. The same goes for Morocco in winter/spring (not shown). But most of the Mediterranean basin undergoes an increase, which is maximum in summer in the southern part and in fall/winter in the northern part. In summer, the relative increase in the 95$^{th}$ percentile of the daily rainfall reaches 20%. However, despite this spectacular increase, the 95$^{th}$ percentile in summer remains well below that in the fall and the risk involved in this increase might be low. Yet in the fall, although lower, the relative increase reaches more than 10% at some spots in the northern part of the basin where the 95$^{th}$ percentile is already among the highest and where flooding events already take place.

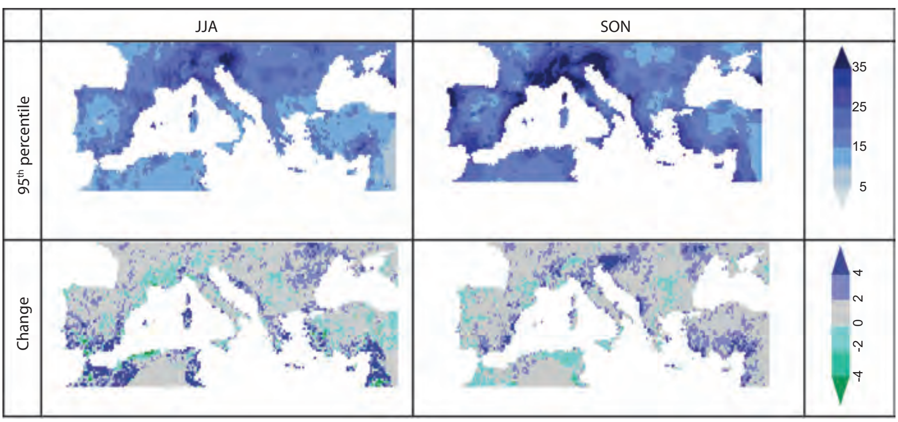


*Figure 2*

*95$^{th}$ percentile of precipitation (mm/day) for the Eurocordex multimodel (12 km resolution) for 1971-2000 (first row) for summer (left) and autumn (right); changes (mm/day) in this percentile during the +2 °C period with respect to 1971-2000 (second row).*

### Regional climate change: variability of the response to socio-economic scenarios

Jacob et al., 2013 reported climate projections at the end of the century (2071-2100) from the new Euro-CORDEX ensemble. They showed a reduced northwards shift of Mediterranean drying evolution and slightly stronger increase in mean precipitation over most of Europe compared to the previous projections of the ENSEMBLE models.

Improvements due to the high-resolution in the EURO-CORDEX simulations are clearly visible in the pattern on change for heavy precipitation events. The projected seasonal mean changes in heavy precipitation for the three emission scenarios (RCP8.5, A1B, RCP4.5) are similar, but some regional differences are visible.

The results of RCP8.5 include a possible decrease of around 25% in heavy summer precipitation over some parts of the Iberian Peninsula and southern France, accompanied by regional increases in parts of Spain and Portugal. For winter, RCP8.5 projects up to 35% increases in heavy precipitation in Central and Eastern Europe, whereas A1B projects changes only up to 25% in the same region.

In this study, both GCM and RCM ensembles show a reduction in weak intensity precipitation and an increase in strong intensity precipitation, and these are more pronounced in the RCP8.5 scenario.

## Conclusions

The first part of this chapter shows how heavy precipitation scales from regional to local scales in the recent past. At local scale, the extreme rainfall trend can increase by a factor of 2 compared to the regional assessment. In the future climate characterized by an increase of about 2 °C in the global temperature, extreme daily rainfall ($95^{th}$ percentile) is expected to increase by about 10% relative to the current level. This is the same order of magnitude as the increase observed at regional scale in the recent past. At the local scale, it corresponds to an increase of 30% to 50% in southern France, for example. Research is underway on the attribution of extreme rainfall trends and of their spatial variability. Efforts will also made to evaluate the new ‘convection enabled’ simulations at kilometric scale that will be performed in Euro-CORDEX/Med-CORDEX in the future and the differences in the way the simulated precipitations respond to climate change  from those simulated by the current lower resolution climate models.

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# Strong winds

## Observed trends, future projections

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## Introduction

The Mediterranean Sea is an almost enclosed basin surrounded by mountain chains with a complex coastal orography and numerous islands, many of which mountainous. The complexity of the physiographic characteristics deeply influences the atmospheric circulation at local scale, giving rise to strong regional wind regimes (see fig. 1) (HMSO, 1962). In the Alboran Sea (the westernmost Mediterranean), the levanter blows from the east and in winter it can be strong and long lasting (up to 10 days). In the western Mediterranean, the north-northwest cold dry mistral and its companion wind the tramontane blow in the Gulf of Lion, occasionally up to the African coasts. The northeasterly strong cold bora affects the entire Adriatic Sea and bora-type winds also occur in the northern Aegean Sea. In this region, storm surges are produced by a regional wind, the westerly southwesterly libeccio, mainly during winter, and the warm and wet southeasterly sirocco is produced mainly in the fall. In the Levantine basin, the prevailing winds are the etesians, strong dry north winds like those that prevail in the Black Sea. The wind speeds associated with these regional wind regimes often reach surface values > 15 m $s^{-1}$ (with gusts of over 20-25 m $s^{-1}$). The Mediterranean basin is also one of the main regions of cyclogenesis in the world and the strongest windstorms are often associated with a cyclone (Lionello et al. 2016).

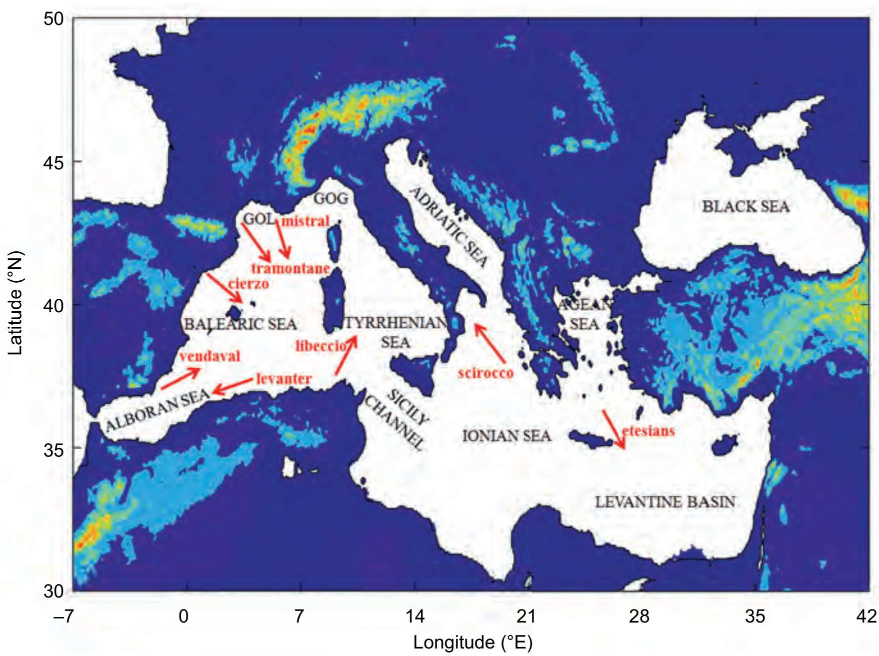


*Figure 1*
*The Mediterranean Basin and its main winds. The names of the main sub-basins are in uppercase letters, and the name of the winds are in red lowercase letters. GOL stands for Gulf of Lion and GOG for the Gulf of Genoa.*

The strongest windstorms and most intense cyclones often produce high impact weather such as storm surges, landslides and flooding. They can also contribute to the rapid spread of forest fires (Hernandez et al. 2015) and create hazardous conditions for sailing, maritime shipping and aviation. They also control the Mediterranean Sea circulation. Indeed, winds like the mistral often produce sea surface cooling, and coastal upwellings, and are the main factor involved in ocean convection and deep water formation (Millot and Taupier-Letage, 2005). The succession of strong wind events partly explains the upper ocean circulation and deep water formation in winter. Finally, these strong and sustained regional winds could be a key to energy production and play an important role in the energy transition as one possible solution for the mitigation of greenhouse gas emissions in the context of global change. How these strong wind systems will evolve in a warming climate is therefore a major question, as any changes in their frequency and characteristics are expected to play a key role in future changes in the Mediterranean regional climate.



## Observed spatial and temporal variability of strong winds

Large-scale climate variability is crucial to European atmospheric circulation, especially the North Atlantic Oscillation, which is the first mode of wind variability in Europe, explaining more than a third of winter variability. It contributes to intense Mediterranean cyclogenesis (Raible, 2007) and therefore largely influences wind extremes over the Mediterranean. In spite of their generally limited size and duration, Mediterranean cyclones are known to cause serious damage in the highly populated coastal areas surrounding the basin, due to the combination of strong winds and heavy rainfall. The majority of intense Mediterranean storms present a dynamical structure equivalent to the one of mid-latitude extra-tropical cyclones (Flaounas et al., 2015). Under certain specific conditions, a few storms may develop into tropical-like cyclones (also known as medicanes), and the associated wind can reach the hurricane strength of 33 m $s^{-1}$ (Cavicchia et al. 2014a). Medicane events occur once or twice a year, mainly in fall and winter in the western Mediterranean close to the Balearic Islands, and in the Ionian Sea (Cavicchia et al. 2014a). Almost all extreme winds in the region are connected with cyclones (Nissen et al., 2010). The spatial pattern of cyclones over the Mediterranean is characterized by several maxima (Alpert et al. 1990; Lionello et al. 2016). Figure 2 shows the locations where cyclones form and cyclone track density in the ERA-Interim reanalysis. The most intense cyclogenesis areas are located in the Gulf of Genoa, south of the Atlas Mountains, close to Cyprus, and in the North Aegean and Black Sea.

Observations of surface wind speed in recent decades reveal an overall negative annual trend over the continents in the Northern Hemisphere, referred to as wind stilling (McVicar et al. 2012). The prevailing hypotheses explaining these trends are changes in surface roughness, changes in aerosol loads or changes in the atmospheric circulation (Jacobson and Kaufman, 2006; Bichet et al. 2012; McVicar et al. 2012). However, wind stilling in the Mediterranean region is minor compared to inter-annual variability, even though negative trends have been found for both etesian wind outbreaks and speed in the eastern Mediterranean (e.g. Poupkou et al., 2011). Nevertheless, at larger scale, and especially for the strongest winds, no consensus concerning the magnitude of the trend or even the sign has been reached as the uncertainties in the different datasets are still too large.

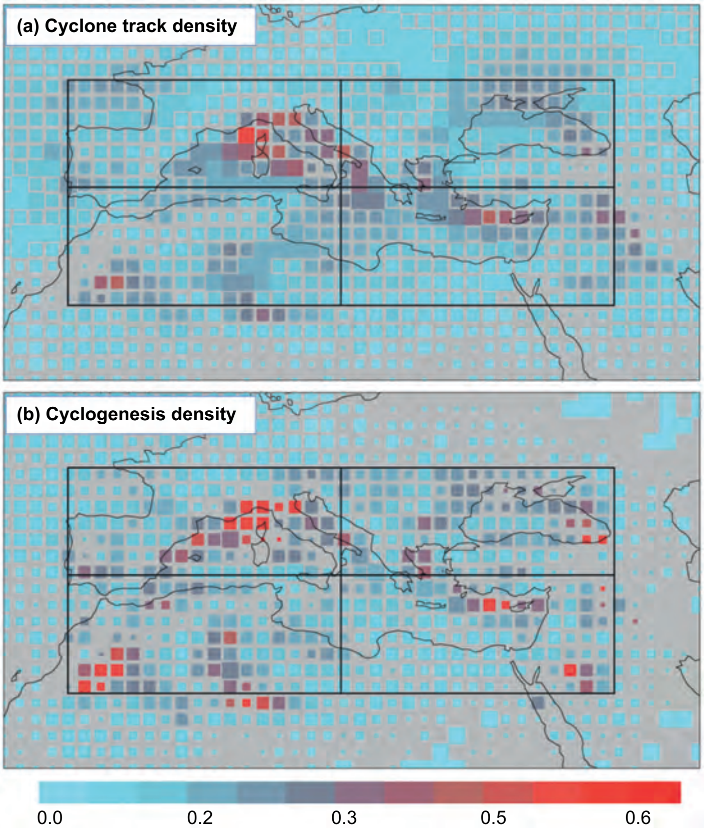


*Figure 2*
*Cyclone track density (a) and cyclogenesis density (b). Colors indicate the probability that a cyclone crosses/forms in each 1.5° x 1.5° cell of the domain in the 6-hourly ERA-Interim reanalyses.*
*Adapted from Lionello et al. 2016.*

Accurately simulating past wind speed variability and trends at scales smaller than 100 km is a prerequisite for future projections of local wind climatology, which relies on downscaling global climate models. Several studies have demonstrated the added-value of downscaling techniques to simulate the strong winds and the cyclonic activity in the Mediterranean region (e.g. Obermann et al. 2016; Vrac et al. 2012).

## Projected changes in wind speed in the context of global change

In the context of expected changes in the 21st century, wind speeds over the Mediterranean region are not expected to be significantly affected by increased greenhouse gas conditions (Rockel and Woth, 2007). The projections of high overland wind speeds in the Mediterranean region, analyzed from eight regional climate models, generally predict wind stilling, in agreement with the findings of Beniston et al. (2007) who suggest a negative change in high wind speed over and south of the Alps or latitude 45°N, locally reaching -10% between the 1961-1990 period and the 2071-2100 period. However the uncertainty remains large as pointed out by Vrac et al. (2012) and Rockel and Woth (2007), who found that the decreasing signal is only captured by all regional climate models during winter months and is only statistically significant in November (see fig. 3). Najac et al. (2009) projected fewer high wind days in southern France whereas Anagnostopoulou et al. (2013) forecast a strengthening of etesian winds associated with the strengthening of the anticyclonic action center, and the deepening of the Asian thermal low over the eastern Mediterranean.

Concerning cyclone-associated winds in the Mediterranean, two factors need to be considered in the context of global change, first, the frequency of cyclones, and second, the intensity of cyclones measured in terms of wind speed. Under climate change conditions, the total number of Mediterranean cyclones is projected to decrease. By analyzing a large number of CMIP5 models, Zappa et al. (2015) found a decrease in the frequency of extra-tropical cyclones throughout the Mediterranean basin as high as 25%, with all models agreeing on the sign of the change. Figure 4 shows the changes in the winter cyclone track density in the most pessimistic emission scenario in comparison with historical simulations. Although fig. 4 shows an overall clear decreasing

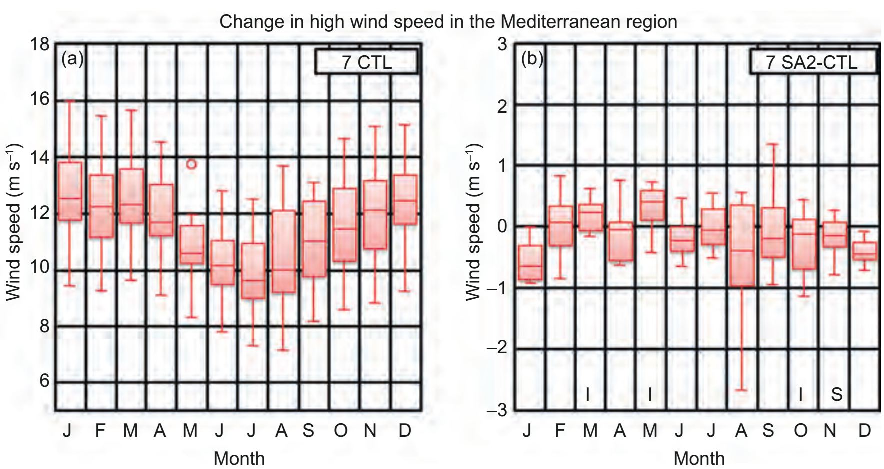


*Figure 3*
*Distribution of 99th percentile of daily mean wind speeds from 8 regional climate models, averaged over the land area of the Mediterranean region. Absolute values for present-day control simulations (CTL) and differences between future scenarios and control runs (SRES/A2-CTL). Open circles denote outliers (i.e. the distance from the lower 25% or the upper 75% quartile is more than 1.5 times the interquartile distance). "S" means at least 6 out of 8 models show statistically significant changes. "I" means at least 6 out of 8 models show changes that are not statistically significant.*
*Adapted from Rockel and Woth, 2007.*

signal for the Mediterranean, in certain areas such as the Levant and near Morocco, cyclones may occur more frequently in the future (Nissen et al. 2014). Concerning cyclone intensity, interestingly there is a signal of opposite sign. Both Cavicchia et al. (2014b) and Romero and Emmanuel (2013) show that the frequency of medicanes will decrease by the end of the 21st century. However both studies agree that more violent storms are to be expected.

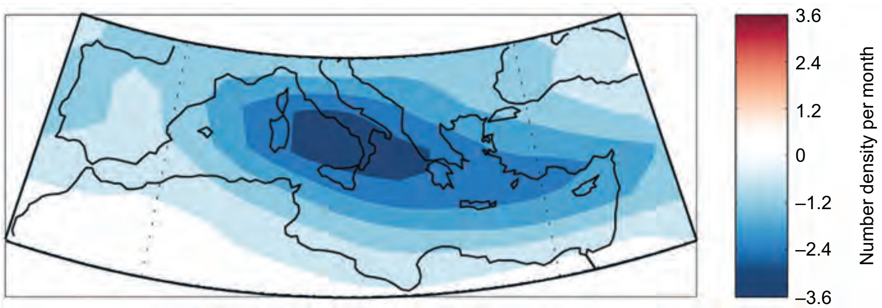


*Figure 4*
*Winter multi-model mean change in the cyclone track density under the most pessimistic emission scenario (2082-2099) compared with historical simulations (1976-2005). Units are the number of cyclones per month per unit area (5° spherical cap).*
*Adapted from Zappa et al. 2015.*

# Consequences

Changes in wind speed in the Mediterranean region will have serious consequences in different fields. A decrease in wind speed can weaken the thermohaline circulation due to both a reduction in wind stress and heat flux (e.g. Somot et al., 2006). Changes in wind patterns can have significant implications for the potential of wind as an energy resource (e.g. Koletsis et al. 2016) and more generally can affect local populations and the economy. Indeed, windstorms and cyclones are the weather events with the biggest impacts in the Mediterranean region, due to the combination of heavy rainfall and strong winds. Because of their small spatial extent, climate models are not yet able to capture all the aspects of future cyclone activity. Despite the expected decrease in cyclone frequency, most studies suggest that high impact weather systems and related wind storms will remain a significant risk in the Mediterranean region.

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Sub-chapter 1.3.3

# Drought: observed trends, future projections

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## Introduction

Drought quantification is difficult since a drought is usually identified by its effects or by its impacts on different types of systems, but no single physical variable can be measured to quantify drought. Droughts are also difficult to pinpoint in time and space since their onset, ending, duration, magnitude, and spatial extent are not easy to define. Thus, drought is often quantified indirectly using indices, which are often based on meteorological, hydrological and/or remote sensing data, and physical models help us understand the relevant processes and make predictions. In this sub-chapter, we describe and discuss drought in the Mediterranean together with some relevant processes, and comment on possible future scenarios.

# Description of drought

## Mediterranean meteorological droughts

The most popular drought indices are those based on meteorological data, such as the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al. 2010) which is obtained using data of precipitation and atmospheric evaporative demand (AED). SPEI informs on the severity of dry conditions and makes it possible to quantify different types of drought and the possible impacts of droughts in a number of sectors. SPEI also makes it possible to identify the main drought episodes that have affected a given region.

As a representative example, figure 1 shows the spatial distribution of the 12-month SPEI in December 2005. In 2005, severe drought conditions were recorded in the west of the Iberian Peninsula, southeast France and extensive areas in Turkey, whereas humid conditions prevailed in the eastern part of the Iberian Peninsula, parts of Italy and the Balkans. This is the common pattern of drought occurrence found in the Mediterranean region, which is characterized by marked spatial variability of drought events, even for the most extreme episodes recorded in the region.

Temporal variability of droughts is also strong. Changes in the average SPEI for four large areas of the Mediterranean region follow very different patterns. In the Iberian Peninsula, the main drought episodes occurred in the 1940s and 1950s and between 1990 and 2012. In Italy and southern France, the main droughts occurred in the 1940s although very strong droughts were also recorded in the 2000s and from 2010 on. In the eastern Mediterranean area, there was a

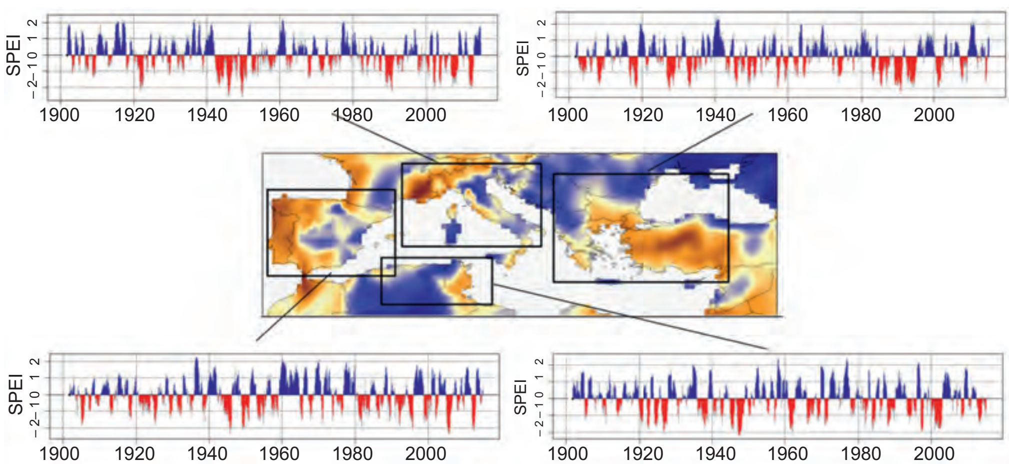


*Figure 1*
*Spatial distribution of the 12-month SPEI in December 2005 (Red indicates dry conditions and blue humid conditions). The average evolution in the SPEI in four representative regions between 1901 and 2014 is also shown. Red: dry conditions, Blue: humid conditions. Source: S. Vicente-Serrano using data from the Global SPEI database (http://sac.csic.es/spei/database.html)*

succession of drought events in the 1930s but the most severe drought events were recorded between 1980 and 1995, a period characterized by extremely severe long lasting droughts. Finally, in northern Tunisia and in Algeria, droughts event have been recorded in different periods but no grouping the drought events in particular decades.

### Long term reconstruction of past hydrological droughts

Hydrological droughts are those related to river flow deficits. Historical meteorological and streamflow observations around the Mediterranean are generally limited to the last few decades and therefore offer a too small sample of extreme events to properly explore their long-term evolution as constrained by both natural variability and recent anthropogenic climate change (Giuntoli et al. 2013). However, recent advances in the reconstruction of the global atmospheric circulation from the late 19$^{th}$ century on provides relevant information on drought precursors that can be translated into local precipitation and streamflow deficits through dedicated hydro-meteorological modeling (Caillouet et al. 2016). Applying these modeling steps to a large set of near-natural catchments over France allowed a better understanding of the individual drought and low-flow events that happened throughout the 20$^{th}$ century. Results revealed drought clusters in specific decades like the 1940s or the 2000s and more widespread events occurring since the 1950s. They also recall somewhat forgotten extreme events like those in 1893 that affected a large part of France, or in 1878 that only affected the Mediterranean coastal area (see fig. 2). Such benchmark events, possibly prefiguring standard 21$^{st}$ century droughts, can therefore inform robust climate change adaptation strategies for water resources management.



## Drought processes and impacts

### Specific Mediterranean drought processes

At least during the warmer months, evapotranspiration is limited by the availability of water, as solar radiation is abundant and water scarce. A good knowledge of soil moisture is thus very important because it determines the availability of water for evapotranspiration. At the same time, vegetation is well adapted to this situation, with strategies to obtain water from deeper soil layers (long roots) along with strategies to better tolerate water stress. Unfortunately, *in situ* observations of soil moisture are rare, but remote sensing is revolutionizing our knowledge of soil moisture and vegetation conditions over large areas, enabling progress in monitoring.

With climate change, an increase in temperature, in the length of the summer dry period and in its extension is expected. This will exacerbate the impacts of drought, as a very dry soil stimulates the sensible heat flux, which can interact

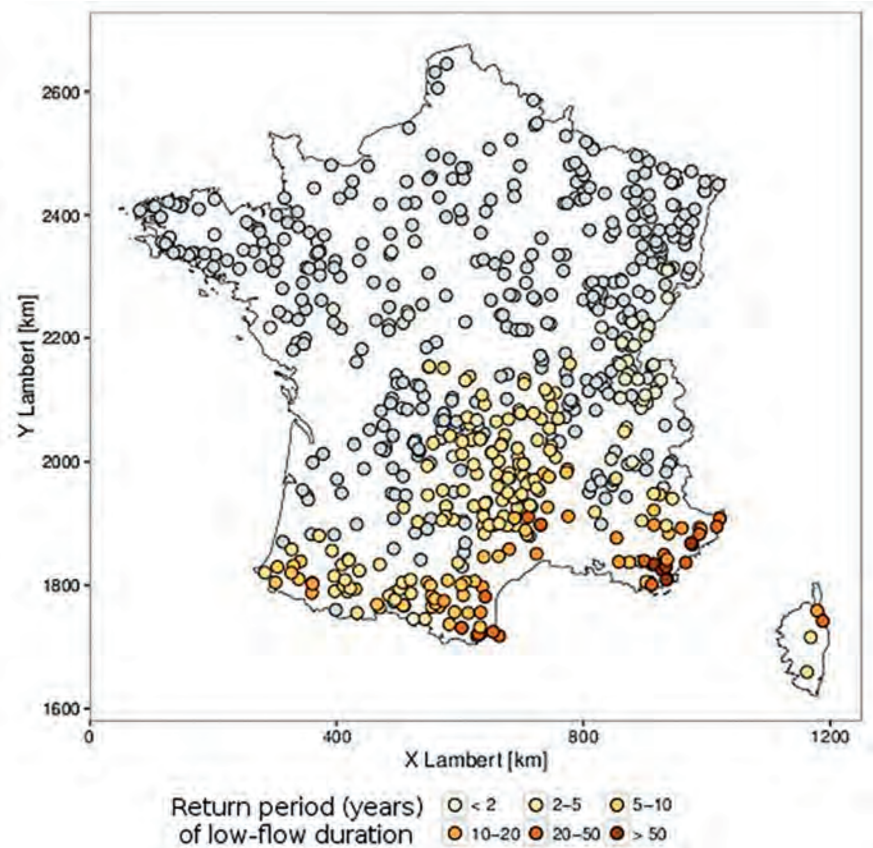


*Figure 2*
*1878 low-flow duration in southern France.*
*Reconstructed by Caillouet et al. (2016).*

with the atmosphere, intensifying heat waves. The vegetation will be water stressed for longer periods too.

In this context, the action of man can also be a vulnerability factor. If climate change increases demand for irrigation, the water available for natural vegetation might decrease due to a drop in the water table caused by pumping water for irrigation, thereby amplifying the above mentioned effect, thereby creating an environment where extreme droughts could thrive.

## Drought and vegetation, as seen using remote sensing techniques

Meteorological drought indices, such as SPEI, are difficult to use in areas with few or no meteorological stations, or in regions with a short period of measurements, which is the case in many Mediterranean areas. Furthermore, even if meteorological indices can be correlated, for instance, with agricultural

Box 1

### Impact of drought on tree growth and health

Increasingly long and severe droughts threaten Mediterranean forests. After decades of improved productivity in the 20th century, since the 1980s, there has been a progressive north-south downward growth trend (Sarris et al. 2011) that reached the northernmost Mediterranean areas at the beginning of the 21st century (Girard et al. 2012).

Thanks to higher temperatures, the growth season starts earlier in spring and ends later in the fall. Some species such as Aleppo pine even show shoot growth and flower development throughout winter. But these additional growing periods are more than offset by the longer stop of growth in summer due to increasing aridity (Adams et al. 2015). This shift in activity is a risk: any even brief period of deep frost in winter can kill the fragile active new tissues or at least damage them, paving the way for invasive pathogens. Higher temperatures during humid periods from fall to spring also favor dangerous fungi and insects such as the processionary caterpillar, which are gaining ground northward and upward in elevation, and unprecedented outbreaks have occurred in recent years. Reproduction processes are also being disturbed. As a consequence, forest dieback episodes have been multiplied by 3 to 4 in the last 30 years in the Mediterranean region (Allen et al. 2010, Fig. 3). Species at the lower limit of their distribution area are particularly threatened, such as Scots pine and silver fir. Repeated droughts also reduce the resilience of Mediterranean forest to wildfires, limiting its ability to regenerate.

*Figure 3*
*Example of forest dieback episode in a Mediterranean environment.*
*Author: M. Vennetier.*

production, a more direct measurement of the impact of drought on vegetation is needed. For this reason, in the last two decades scientists have proposed a number of new approaches for the estimation of drought conditions, based on the use of remotely sensed satellite data.

Optical sensors make it possible to study vegetation dynamics and its variations over time. Most studies are based on the use of the normalized difference vegetation index (NDVI), which is related to photosynthetic activity and whose good accuracy has been demonstrated for the quantification of green vegetation cover or vegetation abundance. The vegetation condition index (VCI) has also been tested at different sites, where it revealed its high potential for the detection and monitoring of drought, and showed a high correlation with agricultural production. The vegetation anomaly index (VAI) also showed a high correlation with precipitation levels over Tunisia.

Microwave remote sensing is also very useful as it measures soil moisture anomalies. The soil water index (SWI) product provided by the Advanced SCATterometer (ASCAT) or other moisture profiles retrieved from the SMOS (Soil Moisture and Ocean Salinity) Mission is essential for this type of discussion, as several studies have shown, including in Tunisia.

The combined use of these remote sensing indices, not only allows us to study drought in areas with few meteorological stations, but also to study how drought propagates to the soil (soil moisture) and to the vegetation and how it impacts agriculture and forestry, for example.

# Future trends

## Future droughts as seen by regional climate models

Regional climate models make it possible to downscale global climate simulations to regions of interest (e.g. the Mediterranean) in order to simulate finer scale physical processes. A simplest way to study drought using regional climate models is to analyze periods of consecutive dry days (dry spells). This was done using a group of European regional climate models (RCMs) (ENSEMBLES project). First, the annual mean dry spell length was studied in the last four decades of the 20$^{th}$ century (1961-2000). Then, the percentage change in the mean dry spell length from these RCMs, forced by different global climate models (GCMs), was analyzed in future conditions (2021-2050) under the A1B emissions scenario. The results showed that RCMs successfully reproduce the general characteristics of the observed dry spells. A north-south gradient of the mean dry spell length index along the Mediterranean basin was obtained in the baseline and historical periods, with the maximum length values located over the Sahara Desert (more than 200 days/year) and minimum over the mountain ranges in the northern part of the basin (with around 3-4 days/year). High values were also observed in the southern half of the Iberian Peninsula, on the western and southern coast of the Mediterranean Sea (over 15 days/year). When climate change projections are analyzed, an overall increase in the mean dry spell length index appears over the Mediterranean basin for all the combinations of GCM/RCM pair simulations, with no clear spatial pattern, suggesting that droughts are more probable in the future. Nevertheless, some uncertainties in the magnitude of the increase emerge among them, ranging from less than 5 to more than 15 days/year, depending on the simulation.

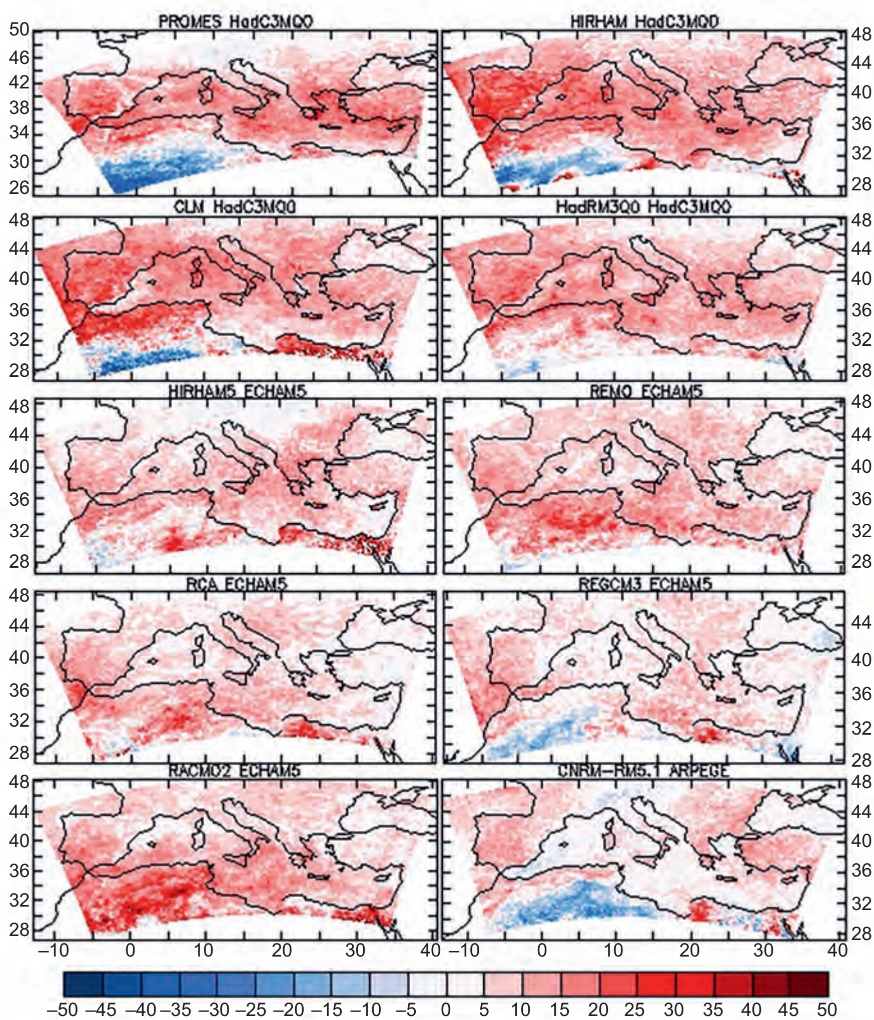


*Figure 4*
*Percentage change (2050-2021) – (1951-1980) in the mean dry spell length under the A1B emissions scenario. RCM/GCM pairs are indicated above each figure.*
*Source: E. Sánchez.*

### Future Mediterranean river flows

Studying the impact of climate change on river flow is difficult due to the uncertainties involved. However, some clear signals emerge. For example, Quintana-Seguí et al. (2010, 2011) studied the impacts of climate change on mean and extreme river flows in French Mediterranean basins in the middle of the 21st century, using a regional climate model, statistical downscaling techniques, and a hydrological model. These studies showed that it is possible to draw general conclusions concerning the expected impacts on the whole region, but that it is very difficult to quantify changes at the basin scale, as most Mediterranean basins are rather small. The studies also showed that there might be significant changes in the seasonality of precipitation over the mountain ranges close to the sea (Cévennes), with increases in some seasons (e.g. winter, spring) and decreases in others (e.g. summer), rendering water management more difficult. In general, a decrease in annual mean precipitation is also possible, causing a decrease in the average discharge, which will be more marked in summer, thereby exacerbating the lack of the resource when it is most needed. Concerning low flow extremes (hydrological drought), low flows are expected to be up to -20% lower almost everywhere in the region. The study revealed a clear signal concerning the increase in the frequency of the low flows, which in the 20th century had a return period of 5 years.

# Conclusions

Drought is a very complex phenomenon involving the atmosphere, soil, vegetation, rivers and underground waters, at different time and space scales. It can be estimated using different indices that make use of meteorological, remote sensing and *in situ* data, the standardized precipitation evapotranspiration index (SPEI) being a noteworthy index. Drought can also be understood and predicted using physical models. In the Mediterranean region, drought is a phenomenon that has major impacts on society. Mediterranean drought displays high spatial variability, thus, when it happens, it does not necessarily affect the Mediterranean region as a whole. Studying extreme drought is difficult, due to relatively short time series of records, as a result, past droughts that lasted longer periods need to be reconstructed to better prepare ourselves for future Mediterranean droughts. This has been done in France with promising results. In terms of processes, the Mediterranean has a marked north-south gradient, which could be modified by climate change. Work is ongoing to improve our understanding of drought events in semi-arid areas. The role of vegetation is very important in this respect, as Mediterranean vegetation is well adapted to drought conditions. Remote sensing allows us to study drought and vegetation even in areas where few measurements are available. Unfortunately, an increase in the occurrence of drought may have negative impacts not only on agriculture, but also on our forests, with increased mortality of trees. In the future, it is expected that the increase in droughts in the Mediterranean region, which may make low river flows more frequent, together with a decrease in mean flow, may increase water scarcity in a densely populated region.



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# Mediterranean extreme floods and flash floods

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## The Mediterranean area is particularly exposed to flash floods

Floods are weather-related hazards and their patterns are likely to be significantly affected by climate change. Floods are already the most frequent and among the costliest and deadliest natural disasters worldwide (Munich RE, NatCat Service; Swiss RE, 2015). This is also true in the Mediterranean area. The EM-DAT international disaster database (http://www.emdat.be/) lists for instance 200 billion Euros damages related to various disasters since 1900 in the countries surrounding the Mediterranean Sea, out of which 85 billion are related to river flooding.

Disastrous flash-floods[1] are much more frequent in some parts of the Mediterranean region than in the rest of Europe (Gaume et al. 2009; Llassat et al. 2010). This is due to the local climate, which is prone to short intense bursts of rainfall. The reliefs surrounding the Mediterranean Sea force the convergence of low-level atmospheric flows and the uplift of warm wet air masses that drift from the Mediterranean Sea to the coasts, thereby creating active convection. In addition, population growth is particularly high along the Mediterranean coasts, leading to a rapid increase in urban settlements and populations exposed to flooding.

The Mediterranean region is a large area extending more than 4,000 km from west to east and 1,500 km from south to north with spatially variable climatic patterns and population densities. It is characterized by diverse climates, synoptic meteorological conditions and hydrological properties: bedrock and soil types, land use and vegetation cover. The flood regimes and the types of dominant flood generating rainfall events vary significantly along the coasts of the Mediterranean Sea (Llasat, 2016). Damaging floods are mainly produced by:

1. Short-lived (often less than 1 hour) strongly convective intense precipitation events (up to 180 mm/h in only 5 minutes) but limited total rainfall amounts (generally less than 100 mm). Such events have a limited areal extent (typically less than 100 $km^2$) and generate local flash floods of small headwater streams. A typical example of such flash floods is the catastrophic flood that occurred in Algiers in November 2001.

2. Mesoscale convective systems can produce stationary rain lasting several hours leading to rainfall amounts exceeding 200 mm in a few hours. In France, up to 700 mm of rainfall within 12 hours was locally recorded during floods in the Aude region in November 1999 and in the Gard region in September 2002. The areal extent of such events ranges from several hundred to several thousand $km^2$. These events mainly occur in fall and affect the north-western coast of the Mediterranean Sea. The flash floods that occurred in Genoa, Italy, in October 1970 and in the Var region of France in June 2010 belong to this category.

3. On some occasions, heavy and sustained rainfall may be part of a large scale perturbation lasting several days. In such cases, extreme rainfall accumulation may be observed locally: 1,500 mm over four days and a record of close to 1,000 mm in 24 hours in October 1940 in the eastern Pyrenees in France. These events cover a large area. Typical examples were the October 1969 heavy rainfall and flash flood in South Tunisia (more than 300 killed) and the October 1940 event that affected both sides of the Pyrenees: the Ter river valley in Spain (90 killed) and the Tech and Têt river valleys in France (44 killed).

1. Flash floods are induced by short duration - from less than one hour to 24 hours - and heavy rainfall convective events – typically 100 mm or more rainfall accumulated over a few hours. The affected areas are often limited to a few hundred square kilometers, with rapid hydrological responses – generally less than 6 hours delay between peak rainfall intensity and the peak discharge downstream.

Total rainfall amounts as well as land use, soil and bedrock types and the initial soil moisture content influence the responses of watersheds to heavy rainfall events and especially their runoff rates: the estimated proportion of the incident rainfall contributing to the observed stream discharges. The runoff rates during flash floods are often limited to 10% to 30%. In some rare cases, when large cumulated rainfall amounts lead to saturation of the watersheds, runoff rates may reach 100% (Marchi et al. 2010). The observed variability of flood frequencies and discharge magnitudes is therefore the result of complex interplay between the characteristics of the generating rainfall events (spatial extent, duration, maximum intensities) and the factors that control the response of the watersheds, especially rainfall rates.



## Sources of information about flood magnitudes and impacts

Information on flood characteristics and magnitudes comes from a wide range of sources (databases, the press, local technical reports) that are incomplete and often not entirely accurate. It is therefore difficult to build comprehensive databases to better understand the spatial pattern and climatology of large flood events. The number of fatalities, sometimes damage estimates, is the type of information that can be collected most easily, mainly from press reports, and is typically the type of information collected in the EM-DAT International Disaster Database (http://www.emdat.be/) or the Dartmouth global archive of large flood events (http://www.dartmouth.edu/~floods/) or in the Italian AVI flood database or the database on Mediterranean floods created in the framework of the HYMEX European research project (Llasat et al. 2013). Re-insurance companies such the Munich Re (CAT NAT Service) and the Swiss Re (Sigma reports) also gather information on damage costs worldwide but which is nevertheless only accessible in a synthetic form. As illustrated in figure 1, such databases should be interpreted with caution. The information collation efficiency is for instance increasing with time and thanks to the improved circulation of information on Internet and the social networks. The EM-DAT seeks to collect information on disastrous events that meet one of the following criteria: at least 10 people killed, 100 people affected, a state of emergency was declared and there was a call for international assistance. Clearly, the number of floods documented in this database has increased since its creation. Can this be interpreted as a sign of a trend? The total number of reported annual fatalities does not show the same trend, suggesting that a larger number of moderate floods have been included in this database in the recent period, but that the number of catastrophic events has not significantly changed. Lasatt et al. (2013) came to the same conclusion.

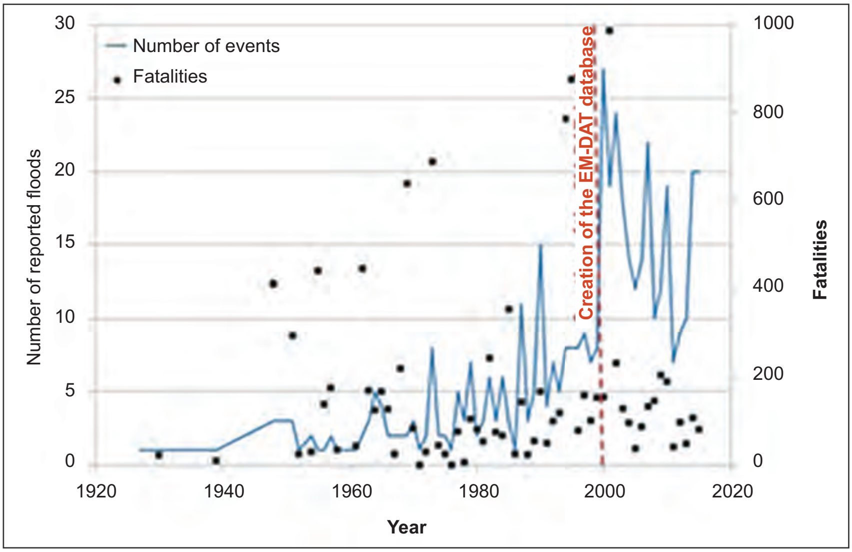


*Figure 1*
*Changes in the number of damaging floods in the countries surrounding the Mediterranean Sea in the EM-DAT database.*
*Source: emdat.be*

Moreover, the amount of damage and the number of fatalities are only indirectly related to the magnitude of the floods and are also strongly determined by local exposure and vulnerability. Both vary in space and over time. Major population and economic growth has taken place along the Mediterranean coast in the past century, with both huge densification and extension of urban settlements outside but also inside flood prone areas. This has led - and continues to lead - to a general increase in flood exposure and in economic vulnerability and costs. At the same time, newly constructed buildings are more resistant to flooding, thereby providing better shelter; warning systems and emergency management has improved and may reduce the number of fatalities. Observed spatial distributions of costs and fatalities are the result of complex interplay between different explanatory factors. It is useful information that reveals the economic and social impact of floods on our societies but its interpretation is questionable.

Flood discharge estimates are therefore indispensable to describe and analyze the geographical patterns of floods, detect possible trends and enable comparisons between countries and sub-regions. But major floods and especially flash floods are difficult to document, as they affect small headwater watersheds that are not monitored. Direct discharge measurements are seldom available and discharge values have to be estimated using indirect methods that may sometimes lead to large errors, especially overestimations, even if significant progress has been made in recent years. Thanks to various European (HYMEX, HYDRATE, FLASH) and national research projects, the number of documented extreme floods has increased significantly in recent years. For the purpose of this paper, we collected information to build a sample of 172 documented extreme floods (Table 1). The database covers the largest floods since 1940 reported in the countries concerned either according to their estimated discharges or to the number of deaths: events with more than 10 deaths were selected when no discharge estimates were available (39 events) except for Greece for which a larger dataset was available.

*Table 1*
*Contents of the database of notable Mediterranean flash flood events for the period 1940-2015.*

| Country | Number of events | With discharge estimates | Sources |
|---|---|---|---|
| Algeria | 20 | 1 | Sardou et al. (2016), Recouvreur (2005), press |
| Egypt | 3 | 0 | Internet and press |
| France | 40 | 38 | Hydrate, recent surveys by the authors, press |
| Greece | 22 | 5 | Hydrate, press, Pappanagiakis et al. (2013), Diakakis et al. (2015) |
| Israel | 11 | 11 | Tarolli et al. (2012) |
| Italy | 46 | 36 | Hydrate, Anselmo (1985), Barredo (2007), recent surveys, press |
| Lebanon | 1 | 0 | Press |
| Morocco | 7 | 7 | Hymex database |
| Portugal | 1 | 0 | Press |
| Slovenia | 1 | 1 | Survey by the authors |
| Spain | 16 | 11 | Hydrate, LLasat et al. (2013), Barredo (2007) |
| Tunisia | 3 | 2 | Press and technical reports |
| Turkey | 1 | 0 | Press |
| **Total** | **172** | **112** | |

Estimated discharge was available for 112 reported flood events. Despite the large number of values available, only one representative value – not necessarily the largest one, as it could be overestimated - was selected for each flood event on any one date in one region. Events including dam failures were not included: the Moulouya valley floods in Morocco (May 23, 1963, 170 killed), the Fréjus catastrophe in France (October 2, 1959, 423 killed), the Vajon dam failure in Italy (October 9, 1963, 2400 killed), and the Val di Stava dam failure in Italy (July 19, 1985, 268 killed).

# Magnitudes and seasonality of extreme floods around the Mediterranean Sea

## Analysis of deaths related to flood events

Figure 2 shows a clear contrast between the reported deaths in the eastern and western parts of the Mediterranean region. The contrast concerns both the spatial density of the events that killed more than 10 people and the average number of deaths per event. This conclusion remains valid even if the two most dramatic events occurred in Algiers (2001, 896 killed) and the town of Rubi near Barcelona in Spain (1962, 815 killed) are removed. Floods generally caused few casualties in the eastern part of the Mediterranean region, with the notable exception of the flood in Tripoli Lebanon on December 17, 1955 (around 160 deaths) induced by a rainfall event of short duration: 100 mm of rain fell on the city of Tripoli and its surroundings in two hours (De Vaumas, 1957).

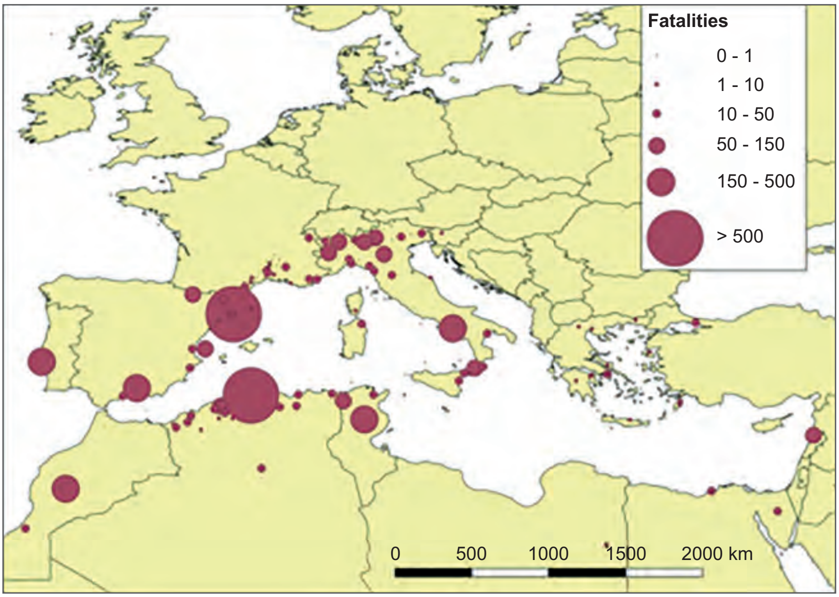


*Figure 2*
*Number of people reported killed in each documentedflood event over the period 1940-2015;*

The contrast was confirmed by analysis of the EM-DAT database (see Figure 3). The average number of people killed each year during river floods ranges between seven in France, most of which in the Mediterranean region, and 30 in Algeria, both western Mediterranean countries, whereas in eastern Mediterranean countries, the number does not exceed two. These figures are also underestimated since moderate floods are not recorded in the EM-DAT database, despite being in the correct range of magnitude. For instance, the average number of people killed due to floods in Greece is four based on comprehensive flood databases established for Greece (Pappagianaki et al. 2013; Diakakis and Deligiannakis, 2015).

## Analysis of major flood peak discharges

The estimated peak discharges of the major floods confirm the observed contrast based on the number of deaths, even if the information concerning eastern Mediterranean countries in the database is not complete (Figure 4). To be able to compare discharge values for a large range of watershed areas and to rate the magnitudes of the reported floods, reduced discharges are mapped in figure 4 according the suggestion of Gaume et al. (2009). The reduced discharge $Q_r$ is the ratio of the discharge value Q ($m^3/s$) to the upstream watershed area A ($km^2$) at a power 0.6: $Q_r = Q / A^{0.6}$.

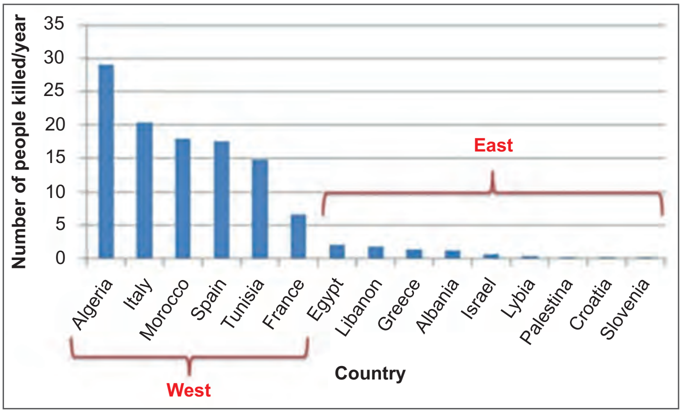


*Figure 3*
*Average number of people reported killed per country and per year by floods over the period 1940-2015 in the EM-DAT database. Source: emdat.be*

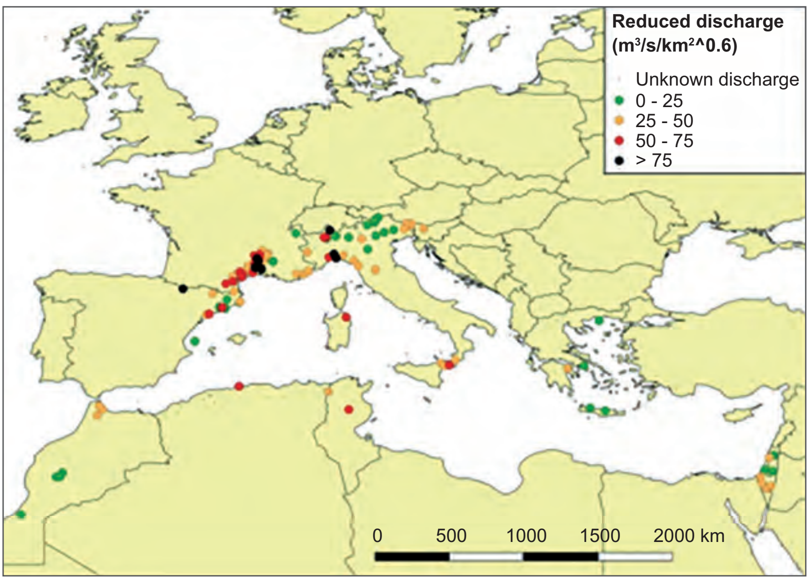


*Figure 4*
*Estimated reduced peak discharge of the documented flood events over the period 1940-2015. The reduced discharge $Q_r$ is $Q/A^{0.6}$, Q is the peak discharge ($m^3/s$) and A is the watershed area ($km^2$).*

Reduced discharges exceeding 50 have only been reported in the western part of the Mediterranean region. Such extreme discharges appear to be more frequent in the north-western Mediterranean region, more particularly in some hot-spots: the Piedmont and Liguria regions in Italy, the Cevennes-Vivarais-Roussillon region in France and Catalonia in Spain. These areas are preferentially affected by longer lasting stationary rainfall events in the fall, leading to high runoff rates and hence high discharge values (Gaume et al. 2009). The spatial heterogeneity of extreme discharge magnitudes is clear in Italy and France, and the flood database is close to complete for these two countries. It needs completing for Spain and North Africa for which only partial datasets are available at the present time.

## Seasonal distribution of extreme flood events

Fall is the main season but not the only one in which extreme floods occur in the Mediterranean region (Figure 5).

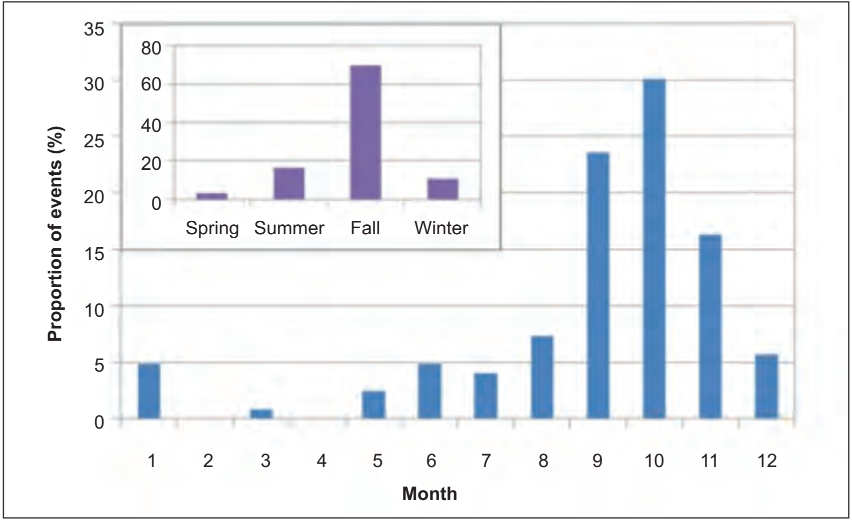


*Figure 5*
*Monthly and seasonal distributions of the documented floods over the period 1940-2015.*

The same seasonal distribution is observed in the eastern part of the area even if it is less pronounced – however, this conclusion is based on an incomplete dataset. The occurrence of summer floods is notable in the Alps and more generally in mountain areas, as illustrated by the Ourika flood in the Moroccan Atlas (August 8, 1995) or the Barronco de Aras flood in the Spanish Pyrenees (August 8, 1996). Spring floods are indeed rare but when they do occur, can have significant impacts, as did the Sarno flood in Italy (May 5, 1998, 147 killed) and the Var floods in France (June 6, 2010, 25 killed). Extreme floods in winter mainly occur in North Africa and Greece.

### Extreme Mediterranean floods compared to world figures

Figure 6 compares the dataset of extreme peak discharges in the Mediterranean region analyzed here with values extracted from other flood catalogues. Some major events are highlighted in the figure to illustrate two facts:

1. The most fatal events (Algiers 2001 and Barcelona 1962) do not necessarily have the largest peak discharge values. This confirms that the local risk is the result of the interplay between hazard – described by the possible magnitude of the peak discharge and local exposure and vulnerability.

2. Few reported world records exceed the proposed envelope curve for the Mediterranean ($Q = 100\ A^{0.6}$). It should also be noted that several past records may have been overestimated (Lumbroso et al. 2012). Some sub-regions of the Mediterranean area, Liguria, Cévennes-Vivarais, appear to be exposed to floods whose magnitudes are comparable to world records.

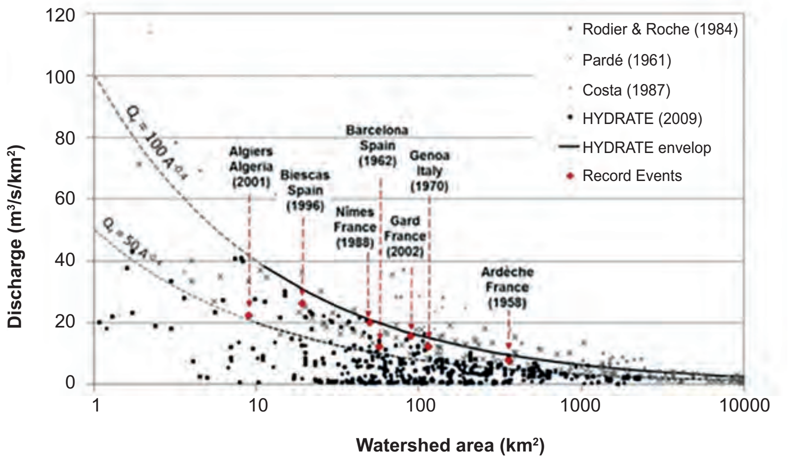


*Figure 6*
*Reported estimated world records from different sources, proposed European envelope curve and some selected European record events since 1940.*

# Observed trends in flood magnitudes and frequency and projections

The numerous studies conducted, especially in Europe, report contrasted trends for extreme streamflow with both positive and negative trends, with variable statistical significance and no clear structured pattern (Madsen et al. 2014). There are no clear national or large-scale regions in Europe with uniform statistically significant increases in flood discharges in recent years, although some trends appear for smaller regions.

Figure 7 illustrates the type of results of trend detection studies in France: trends in annual maximum peak discharges (Giuntoli et al. 2012). The analysis was based on a rich dataset of 209 stream gauge measurements covering the period 1968-2008 and two statistical tests conducted on each individual series (local test) and on regional samples of series to gain robustness (regional test). A limited number of series or regions showed a statistically significant trend. It is interesting to note a general and unexpected decreasing tendency in southern France that is spatially consistent if not statistically significant. The main conclusion is that if some trends exist, they are almost impossible to detect due to the limitations of the available datasets, especially on extreme events. Likewise, recent streamflow projections based on Euro-Cordex climate projections led to significant forecasted changes in river flood frequencies in Europe but to less clear results for the Mediterranean region (Alfieri et al. 2015).

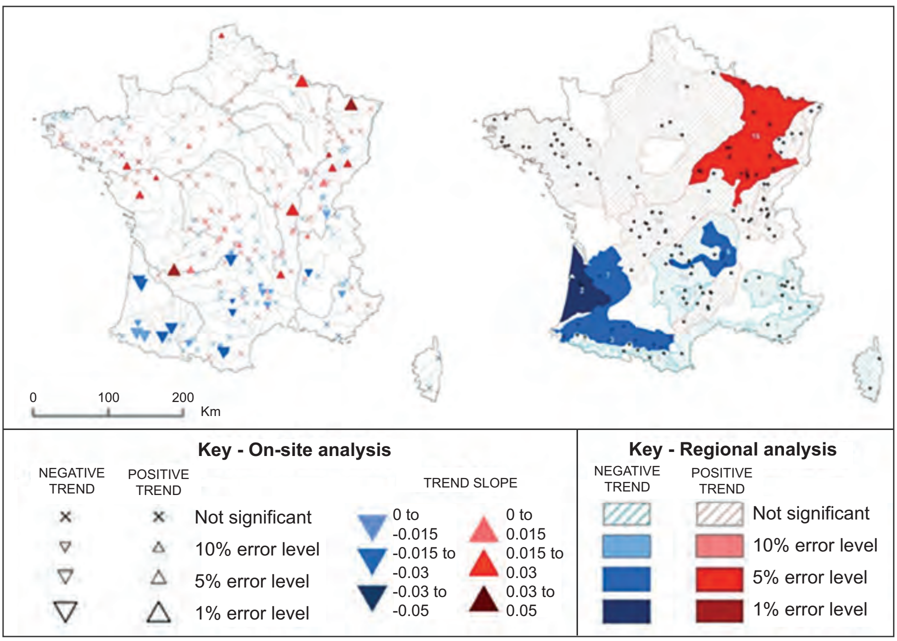


*Figure 7*
*Trends in annual maximum streamflow in France based on local and regional tests (Giuntoli et al., 2012).*

# Conclusions

Our knowledge of floods in the Mediterranean area has advanced substantially in recent years thanks to the development of databases and focused research programs. A general pattern of the spatial and seasonal distribution of flood magnitudes can now be established as reported here. The main characteristics of the floods around the Mediterranean Sea are the following:

1. The magnitude and impact of extreme floods vary significantly over the Mediterranean region with a clear contrast between west and east. The western part of the area is much more exposed to high impact and high magnitude events. This is probably due to the proximity of the Atlantic Ocean and oceanic climatic influences at latitudes where eastward atmospheric flows dominate.

2. Some sub-regions, including Liguria and Piedmont in Italy, Cévennes-Vivarais-Roussillon in France, and Catalonia and the Valencian province in Spain are particularly exposed to extremely severe floods whose peak discharge values may be close to world records. This particular pattern is the result of the interplay between the dominant atmospheric low level flow circulation patterns and the relief and orientations of the northern Mediterranean coast, which force convergence and trigger convection (Ducrocq et al. 2014).

3. Fall is clearly the main season - but not the only season - for extreme and damaging floods. This is particularly the case of mesoscale convective systems producing long lasting and stationary rainfall events that lead to strong responses by the watersheds concerned (i.e. high runoff rates due to soil and subsoil saturation) and to extraordinary peak discharge values.

4. No significant trend was detected in the frequency and magnitude of extreme floods in the Mediterranean region to date, probably due to the limitations of the available datasets and some complex overlapping signals (e.g. decadal and inter-decadal variability). Likewise, the existing projections do not clearly point to a change in extreme flood patterns in the Mediterranean region linked to climate change. But, whatever the case may be, the risk of flooding is likely to increase due to population growth and urban development in flood prone areas in the coming years.

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Chapter 4

# Air quality and climate in the Mediterranean region

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# Abstract

Ambient air ranks number one among the natural resources vital to human beings, with an average individual daily need of 12 kg. Due to the specificities of the Mediterranean region (sunny, hot and dry climate; long-range transport converging over the basin), air pollution in reactive compounds over the Mediterranean is often higher than in most European inland regions. Climate change (increase in temperature and drought) and anthropogenic pressure (growing population) should significantly impact the regional air quality. As a result, Mediterranean inhabitants who are already regularly exposed to pollutant loads well above WHO air quality recommendations will be further exposed, resulting in an excess of premature deaths. Exposure monitoring and win-win strategies should be developed in the future both to improve air quality and develop a low carbon economy. The evolution of emissions under climate change is not always clear and much uncertainty remains around present emissions from large urban-industrial centers, although recent progress has been made on emissions of the different regional sources of pollutants. It has been established that the regional climate and water cycle are affected by atmospheric chemistry. By reducing solar radiation at the surface, aerosols reduce the yearly average precipitation in the Mediterranean by 10%, which is a major issue since water is already scarce. Aerosols could further reduce precipitations by reducing the size of cloud droplets or through the formation of cloud droplets and ice crystals. Moreover, recent *in situ* and model experiments indicate that anthropogenic nitrogen and desert dust phosphorus deposition in nutrient-depleted surface seawater favors phytoplankton development, which stimulates the sink of atmospheric $CO_2$ into marine sediments. But Saharan dust deposition by rain also stimulates bacterial growth, which reemits $CO_2$. The net effect of desert dust deposition at large scales needs to be established.

# Résumé

L'air est sans aucun doute la ressource naturelle la plus essentielle à l'homme : chaque jour 12 kg d'air sont nécessaires à sa survie. Du fait des spécificités de la région méditerranéenne (climat ensoleillé, chaud et sec ; convergence de masses d'air d'horizons lointains), la pollution de l'air en espèces réactives y est souvent plus forte que dans la plupart de l'Europe continentale. Les changements climatiques (augmentation des sécheresses et de la température) et la pression démographique devraient dégrader encore la qualité de l'air. En conséquence, les habitants de la Méditerranée qui sont déjà régulièrement soumis à des niveaux de pollution bien au-dessus des recommandations de l'OMS devraient se trouver plus exposés encore, ce qui engendrera une surmortalité. Un meilleur suivi de l'exposition des habitants et des solutions « gagnant-gagnant » devraient être mises en place dans le but d'améliorer la qualité de l'air et de s'engager dans une économie décarbonée. Les conséquences des changements climatiques sur les émissions de polluants par les principales sources régionales ne sont pas toujours très claires. Il a été établi que le climat régional et le cycle de l'eau sont altérés par la chimie de l'atmosphère. En réduisant le flux solaire en surface, les aérosols réduisent les précipitations moyennes annuelles de 10 % en moyenne sur le bassin méditerranéen, réduisant un peu plus une ressource déjà rare. Les aérosols pourraient réduire plus encore les précipitations en réduisant la taille des gouttes d'eau dans les nuages ou en agissant sur la formation de cristaux de glaces. Par ailleurs, de récentes expériences indiquent que le dépôt atmosphérique d'azote et le phosphore issu des poussières désertiques à la surface des eaux pauvres en nutriments de la Méditerranée favorise le développement du phytoplancton activant par la même occasion l'absorption de $CO_2$ par l'océan. Cependant, il a aussi été observé que le dépôt de poussières favorise le développement de bactéries qui elles-mêmes rejettent du $CO_2$ du fait de la respiration. L'effet net du dépôt de ces poussières à grande échelle reste à établir.


# Introduction

In this chapter, we consider relatively short-lived (<~1 month) particulate and gaseous tropospheric trace species that cause atmospheric pollution and have two-way interactions with climate. Emissions of long-lived greenhouse gases and their role, and evolution with climate change are dealt with elsewhere in this book.

Ambient air is one of our vital natural resources. Air quality in the Mediterranean region is generally poor, due to both particulate and gaseous pollution. For instance, particulate or ozone concentrations are generally higher in the

Mediterranean region than in most continental European regions, especially during the long dry and sunny summer season that characterizes the Mediterranean type of climate, (e.g. Nabat et al. 2013; Doche et al. 2014; Menut et al. 2015). In addition, the Mediterranean region is a hot-spot for climate change (Giorgi and Lionello, 2008), whereas numerous two-way interactions take place between climate and air quality, which are not always well understood. In addition, the Mediterranean region is expected to undergo a major increase in population, especially the development of large urban centers on its eastern and southern sides (CIHEAM, 2009). Air quality is already very poor in such centers and has significant adverse effects on health (an average of more than 20 deaths per 100,000 inhabitants took place in 2008 in Egypt, Greece, Israel, Lebanon, Turkey; WHO, 2014). It is thus important to understand the impact of the expected climate change on atmospheric chemistry and the resulting surface air quality in the Mediterranean region (Colette et al. 2013).

Conversely, atmospheric pollution also affects the climate. The most obvious effect is global warming due to anthropogenic emissions of greenhouse gases (GHG), but anthropogenic aerosols and ozone, for instance, also perturb the Earth's radiative budget (IPCC, 2014). Up to now, future climate predictions have neglected feedback due to atmospheric composition, apart from that due to long lived GHGs. Atmospheric pollution, however, is also made up of many gaseous and particulate species that are more chemically active than GHGs and these short-lived species have various reciprocal interactions with climate, which must be accounted to better simulate their combined evolution. For instance, direct effects due to scattering and absorption of solar radiation by tropospheric anthropogenic aerosol particles compensate for and even cancel out the warming effect of GHG emissions in polluted regions at the regional scale (Bergamo et al. 2008). But they are much more difficult to represent in climate models (i) because of the high temporal and spatial variability of their concentrations and optical properties whereas, in comparison, GHG vary very little in concentration (Le Treut et al. 1998), and (ii) because to properly assess aerosol climatic impact, it is necessary to use coupled atmosphere-ocean dynamical models rather than fixed sea-surface temperature to account for a radiative impact that affects sea surface evaporation (Nabat et al. 2014). These reactive species form secondary products that are not directly emitted into the ambient air but control the concentration of fine particles in the background (Querol et al. 2009) and urban (El Haddad et al. 2011) Mediterranean air, they can be transported over long distances in the troposphere (Lelieveld et al. 2002; Ricaud et al. submitted) and affect air quality at the surface (with profound impacts on human health) (Künzli et al. 2000), perturb the radiative budget of the atmospheric column and modify cloud properties with significant consequences for the atmospheric water cycle and climate (Nabat et al. 2015), affect marine biogeochemistry (Guieu et al. 2014a) and continental vegetation (Paoletti, 2006) through their deposition at the Earth's surface. There are thus many processes and different types of feedback to take into consideration when assessing interactions between air quality and climate and when modelling the present and future coupled air quality-climate system.

The present chapter is a contribution from the project ChArMEx (the Chemistry-Aerosol Mediterranean Experiment; http://charmex.lsce.ipsl.fr) of the multidisciplinary regional research program MISTRALS (Mediterranean Integrated Studies at Regional and Local Scales; http://mistrals-home.org) endorsed by ALLENVI. It summarizes current knowledge on the links (feedforward and feedback) between climate and the air resource in the Mediterranean region, on the impact of expected climate change and increasing anthropogenic pressure on that natural resource and its consequences for human health, highlighting on-going efforts and recommended research to overcome critical limitations of our present knowledge. In the following sub-chapter headed 'Sources of reactive species and source apportionment', we review emissions that affect the Mediterranean atmospheric environment and report source apportionment results in both coastal urban and background air. In a separate text box, we also present the regional emission database ECCAD/ChArMEx dedicated to the Mediterranean region. We describe the particular cases of large urban centers, aeolian erosion, and biogenic emissions of volatile organic carbonaceous species. In the sub-chapter headed 'High concentrations of aerosols and pollutant and greenhouse gases', we address the question of the high atmospheric loads of atmospheric pollutants in the Mediterranean region and our understanding of the reasons. We include a focus on secondary organic aerosols, a major component of fine particles in the ambient air and a challenge for atmospheric chemistry models because they are formed by complex chemical reaction chains from gaseous compounds emitted by both human activities and natural sources. The sub-chapter headed 'Atmospheric deposition to nutrient-depleted seawater' is dedicated to the deposition of aerosol particles to the oligotrophic Mediterranean Sea, a major pathway for the transfer of nutrients and contaminants, and its impact on surface marine ecosystems. The sub-chapter headed 'Impact of atmospheric chemistry on the regional climate' describes the impacts of atmospheric chemistry on climate and reviews recent results on their assessment. In the sub-chapter headed 'Impacts of air quality on health in the Mediterranean region', we report recent results on the detrimental effect of air pollution on human health. In the sub-chapter headed 'The (uncertain) future of air quality', we question our knowledge on the evolution of air quality in the coming decades. Finally, we summarize the main recent advances, open questions and related ongoing research and perspectives.

# Sources of reactive species and source apportionment

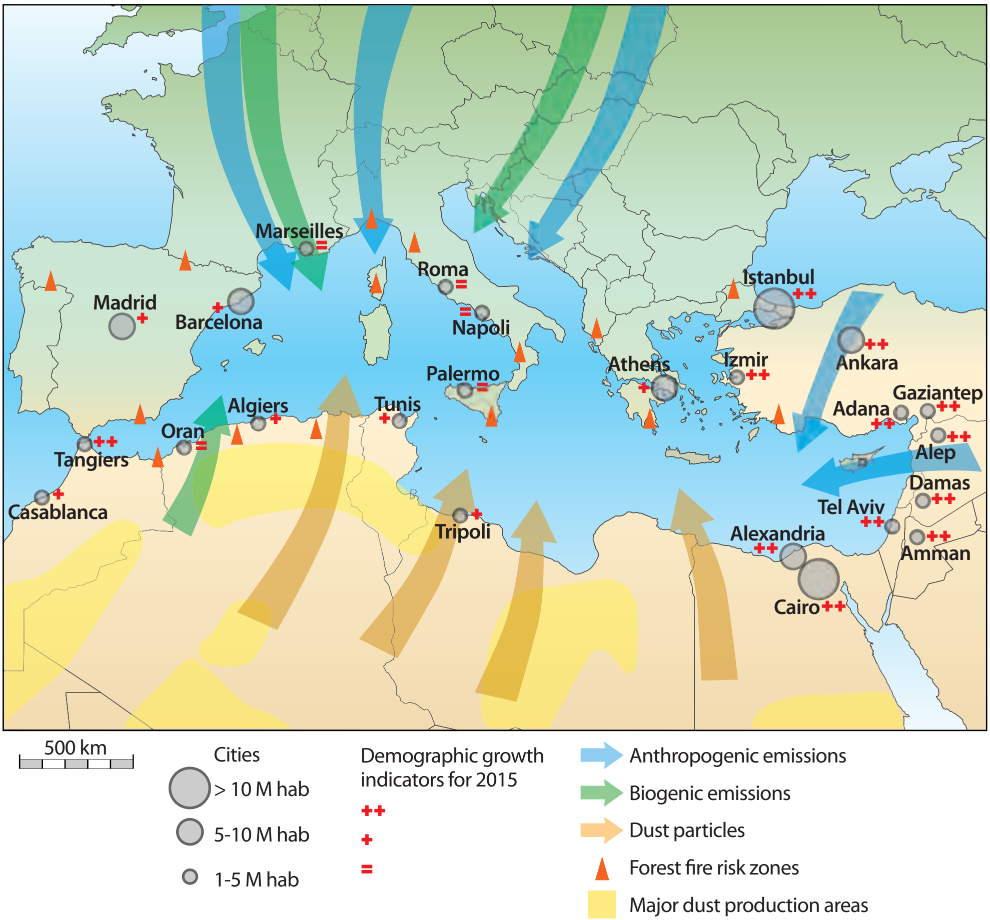


*Figure 1*
*Variety of continental sources impacting the Mediterranean basin.*

Natural and anthropogenic emissions of gaseous and particulate pollutants are key factors in air quality degradation and climate change. As indicated by the Latin origin of the name Mediterranean ("the middle of the lands"), the Mediterranean basin is a receptor of anthropogenic emissions from eastern Europe and surrounding coastal urban areas combined with wind-driven dust from the Sahara and Arabian deserts, biogenic emissions from the surrounding vegetation, and sea salt [Kanakidou et al. 2011; Fig. 1].



# Natural sources

Natural sources play a key role in the exchange of compounds between the Earth's surface, the oceans and the atmosphere. The species emitted are characterized by high diversity and potentially high chemical reactivity. Consequently they have direct and indirect impacts on climate and air quality.

## Marine sources

The sea surface produces airborne particles that contribute to the aerosol load, Earth's albedo, climate, and air quality in marine environments. There are large gaps in our knowledge of marine emissions, which, in turn, are responsible for large uncertainty on our future climate (Carslaw et al. 2013). *Marine primary aerosols* are produced by bubble bursting processes, mostly under the influence of wind-driven wave breaking mechanisms. Primary marine organic particles consist of microbiological organisms (including viruses and bacteria), biological debris, exudates and by-products. *Marine secondary aerosols* are formed by condensation of gas-phase species emitted from the seawater. Secondary organic aerosol (SOA) particles are expected to result from the atmospheric oxidation of biologically driven emissions of volatile organic compounds (VOC), which have not yet been clearly identified. Among the formation pathways of secondary aerosol particles, nucleation is the process responsible for the formation of new nanoscale particles (as opposed to the process of condensation onto pre-existing particles). Triggered by photochemical processes, new particle formation (NPF) takes place as an "event" that lasts several hours, during which the concentration of the clusters of nanoparticles increases to high levels by nucleation. These clusters grow rapidly to a few nanometers in size when they can be detected. NPF is expected to generate a large number of aerosols, which, in turn, can affect climate by influencing cloud radiative processes (Spracklen et al. 2006). Questions are still open concerning the conditions that favor the occurrence of NPF and particularly the type and the origin of precursors. How are VOC emissions and nucleation events influenced by

### Box 1
### ECCAD/ChArMEx regional Mediterranean emission database

The production of the ChArMEx state-of-the-art specific regional emission inventory for the preceding decade began in 2011 using the most recent literature, starting with yearly anthropogenic fossil and biofuel emissions in southern Europe from TNO (Kuenen et al. 2011; Liousse et al. 2014) completed by estimates for northern Africa (Assamoi & Liousse, 2010; Liousse et al. 2014). It was further completed with key emissions from agricultural and forest biomass burning (Turquety et al., 2014), soils for dust (Callot et al. 2000) and for $NO_x$ (Yienger & Levy 1995), aircraft (Riahi et al. 2007), shipping, volcanoes (Andres & Kasgnoc, 1998), sea surface (Schwier et al. 2015), and vegetation (Guenther et al. 2006). The domain of interest extends from 10°N (tropical Africa) to 70°N (northern Europe) and from 20°W (Iceland) to 50°E (Caspian Sea) sometimes with a spatial resolution of 10 km. Fig. 2 summarizes the content of the database.

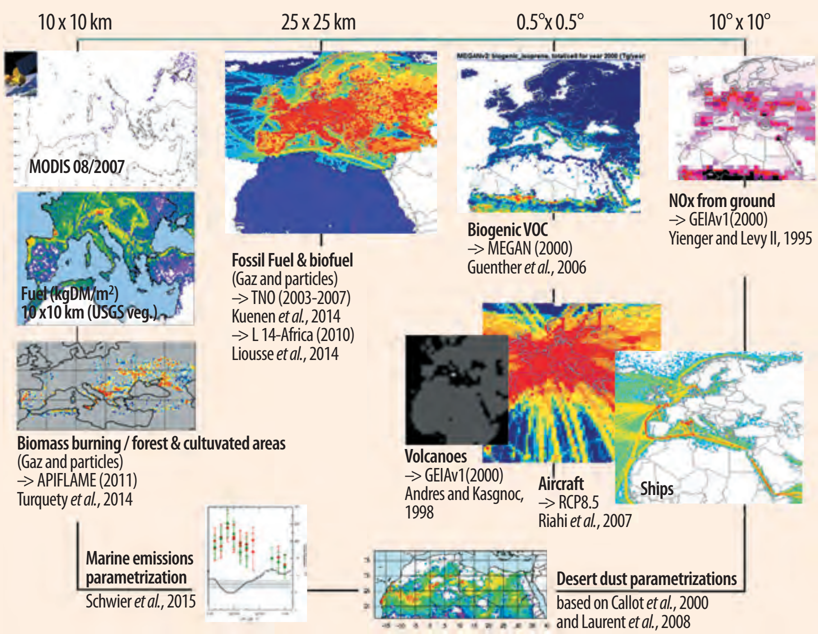


*Figure 2*
*The different emission subsets and emission parameterizations available in the ECCAD/ChArMEx regional emission inventory (http://www.aeris-data.fr/redirect/eccad/ChArMEx).*

water composition (clean or polluted seawaters), biological composition and activities? In the framework of ChArMEx, marine aerosol emissions to the atmosphere have recently been studied in two research projects, MEDSEA (MEDiterranean Sea Acidification) and SAM (Sources of marine Aerosol in the Mediterranean atmosphere). Both used mesocosms, i.e. semi-opened chambers containing natural seawater and an atmospheric headspace. Results showed a clear correlation between the level of seawater chlorophyll *a* (Chl-*a*), measured as the standard proxy for phytoplankton biomass, and the amount of organic compounds in airborne particles produced during the wave breaking process (Schwier et al. 2015). This result is in agreement with parametrizations obtained in the Atlantic Ocean combining Chl-*a* levels measured by satellite and the organic fraction of ambient marine aerosol measured at receptor sites (Rinaldi et al. 2013). Seawater biology also influences gas phase emissions, and the number of particles formed from some of these gas phase species by nucleation. SAM experiments showed that some VOC emissions increase during phytoplankton blooms. In parallel, several nucleation events were seen to be initiated from seawater emissions both in the mesocosms and in laboratory experiments. The experiments also identified iodine species that trigger the formation of new particle clusters after they reach a threshold concentration, and excluded the usually suspected precursor dimethyl sulfide (DMS) in the northwestern Mediterranean region investigated (Sellegri et al. 2016). Another result revealed that emitters of iodine species are not linked to Chl-*a* as expected, but to other biological tracers. Furthermore biologically driven emissions of amines appear to contribute strongly to early growth of the cluster in the 1-10 nm size range. These findings advance our understanding and our ability to model the complex climate feedback loop that involves temperature, biological populations in the seawater and marine aerosol emissions.

## Emissions from vegetation

Ecosystems are a notable source of a wide variety of reactive volatile organic compounds (VOCs), biogenic VOCs (BVOCs), such as isoprene, monoterpenes, methanol, and many others. BVOC emissions largely dominate anthropogenic VOC emissions at the global scale. BVOCs play a key role in atmospheric chemical processes particularly in the ozone cycle and in the formation of secondary organic aerosols (SOA). Due to high temperatures, high levels of solar radiation, and high biodiversity, to which BVOC emissions are very sensitive, the Mediterranean region is a major source of BVOCs (Owen et al. 2001), and has a significant impact on ozone and aerosol formation (Sartelet et al. 2012). Models of the correct meteorological and chemical conditions that are able to reproduce the diurnal variation in isoprene emissions (Guenther et al. 2012) are needed to understand the underlying atmospheric photochemistry.

Large uncertainties persist in the composition, distribution and levels of BVOC emissions. Both experimental and modeling studies are thus crucial to improve our knowledge, especially in the context of climate change that is projected to severely impact the Mediterranean region. As part of the ChArMEx project, a thorough case study was performed at the OHP Oak Observatory (Haute Provence, France) in a coppice of downy oak, a widely represented tree species in the Mediterranean area. Measurements from the branch (GENARD-ZIELINSKI et al. 2015) to the canopy scale confirmed high isoprene emissions (up to almost 10 mg $m^{-2}$ $h^{-1}$), significant methanol emissions (up to 0.63 mg $m^{-2}$ $h^{-1}$), and negligible monoterpene emissions (KALOGRIDIS et al. 2014). The isoprene degradation within the canopy was found to be very low (<3%) due to the low level of $NO_x$ and the low canopy height (KALOGRIDIS et al. 2014). Measurements showed that isoprene emissions increased with an increase in radiation and air temperature, and latent heat flux was also shown to be a useful parameter to explain variations in isoprene emissions (Baghi, 2013). A study of the potential impacts of climate change on water resources (namely a 30% water deficit, as foreseen for the year 2100) suggests a significant increase in isoprene emissions in the future, irrespective of the warming scenario (GENARD-ZIELINSKI et al. submitted).

Atmospheric chemistry is being modeled to simulate the fate of BVOC emissions on a typical hot sunny day (July 3) of the 2014 ChArMEx airborne experiment above the OHP. Preliminary results show that strong diurnal emissions of BVOC lead to a clear SOA formation event.

## Aeolian erosion/soil dust emissions

Dust emission results from the erosion of soil by wind (BAGNOLD, 1941; GILLETTE, 1981), which mainly occurs in the arid and semi-arid regions of the Earth, the Sahara desert and its fringes being considered as the main source region in the world. The resulting aerosols both scatter and absorb solar and Earth radiations, which affect the Earth's radiative budget. When deposited on the Earth's surface, mineral dust contributes to the input of growth-limiting macro and micro nutrients to oceanic surface waters (see the dedicated sub-chapter hereafter) and terrestrial ecosystems.

In North African countries, the rapid increase in population has led to a growing demand for agricultural products. As a result, the pressure on natural resources is increasing steadily with the expansion of cultivated areas stimulated by the introduction of modern plowing techniques. Beginning in the 1960s, the disc plow pulled by powerful tractors has progressively replaced the traditional mold board plow pulled by draft animals, which affects dust emissions.

As can be seen in Fig. 3, wind erosion is more than one order of magnitude greater on land tilled with a disc plow than in fields tilled with a mold board plow, land prepared with a tiller being between the two. These results strongly suggest that new tillage techniques such as using a disc plow drastically increase soil erosion by wind in agricultural fields with loose soils. They also confirm that traditional tillage tools like the mold board plows are the most suitable tillage tools to preserve soils in semi-arid agricultural regions. Finally, these results suggest that dust emissions from North African countries are increasing because of changes in land use management rather than because of the extension of the cultivated area. For example, YOSHIOKA et al. (2005) suggest that this type of land preparation could now be responsible for up to 25% of North-African dust emissions.

A monitoring station was recently set up close to Medenine (southern Tunisia; http://193.95.22.108/) for the long term monitoring of the surface atmospheric concentration and atmospheric column load of soil dust, and of the dust deposition flux.

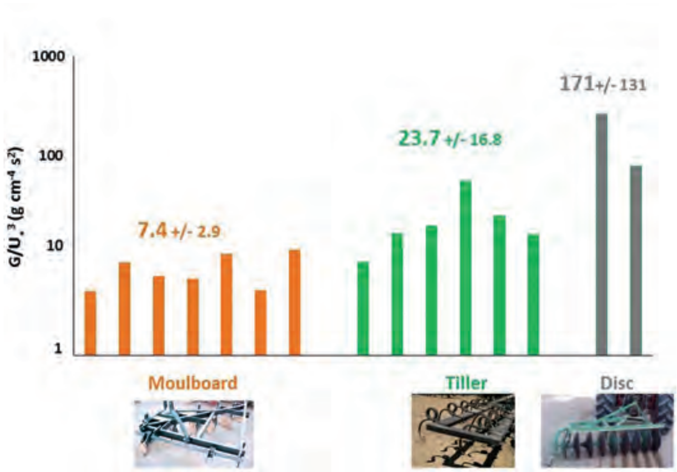


*Figure 3*
*Normalized horizontal flux (G) of sediments eroded by wind in fields prepared by three different types of plow used in Tunisia (adapted from LABIADH et al. 2013).*

# Source apportionment

## Urban areas

The coastal areas of the Mediterranean include megacities like Cairo (12 million inhabitants), Istanbul (12 M), Athens Great Area (5 M), and Barcelona (5 M). All these cities are subject to heavy gaseous and particulate pollution. The population of these regions will continue to increase, especially in the eastern part of the basin, leading to a higher anthropogenic pressure in a context of climate change.

Satellite images of nitrogen dioxide columns from SCIAMACHY identified coastal urban areas in the Middle East as hot-spots of pollution in the region (LELIEVELD et al. 2009). Global emission inventories all agree on a marked increase in anthropogenic emissions of major pollutants ($NO_x$, VOC and $PM_{2.5}$) in the Middle East Area (MEA), in contrast to what is observed in post-industrialized regions like Europe and the USA. In the coming decade, anthropogenic emissions from MEA are projected to be even larger than those from Europe and the USA (Salameh et al. submitted).

Anthropogenic emission inventories provide key input data for the atmospheric models used for the prediction of air quality and for the study of the most efficient regulations to reduce air pollution. The quality of emission inventories from rapidly growing megacities in the southern and eastern Mediterranean is of concern because local emission data are sparse. A new road traffic emission inventory was built for Algiers, where road traffic is a major source of atmospheric pollution. It was validated by comparing high resolution (4 km) simulations with the regional atmospheric chemistry and transport model CHIMERE and observed air quality measurements of NOx and CO (Rahal et al. 2014). Some highly resolved inventories have also recently been developed at the regional scale for Beirut (Waked et al. 2012) and Istanbul (Markakis et al. 2012), but their uncertainties are unknown. As part of the TRANSEMED initiative supported by the MISTRALS/ENVIMED program, a source-receptor methodology was developed for emission inventory evaluation. The approach consists in combining existing and newly collected observations and complementary source-receptor approaches (i.e., urban enhancement emission ratios, multivariate models like positive matrix factorization, PMF) in large urban areas like Beirut (Lebanon), Istanbul (Turkey), and more recently Athens (Greece) and in the near future, Cairo (Egypt). Very detailed databases of ambient and near-source observations are being built with a focus on the composition of gaseous organic carbon. The results recently obtained for Beirut (Salameh et al. 2014, 2015, 2016) showed (i) the extremely high levels of pollution for organics, (ii) the dominant effect of traffic emissions on concentrations of VOC, (iii) the poor spatial variability of speciated NMHC traffic emissions regardless of the region, and (iv) the high uncertainty and discrepancies between large scale emission inventories compared to observational constraints and local scale inventories (see also Abdallah et al. 2016).

## Source apportionment at the regional scale

Sources impacting the Mediterranean basin can be apportioned at regional scale using models that exhaustively account for all the processes (emission intensity, chemistry, air mass transport) that occur between the sources and the receptor zones. This approach has been applied for the summer (JJA) 2012 period at a resolution of 50 km using the chemistry-transport model CHIMERE dynamically forced by the model WRF (Rea et al. 2015). The contributions from different sources of particles and gaseous precursors to both the surface particulate air quality ($PM_{2.5}$ and $PM_{10}$) and the aerosol optical depth (a proxy of the aerosol concentration in the vertical column) were determined by eliminating particle sources one by one (anthropogenic, fire, soil dust, vegetation, sea), and comparing the results with the reference simulation with all the sources activated. Results showed that desert dust had the most influence on surface PM concentrations in the Mediterranean basin (up to 86% of $PM_{10}$) followed by anthropogenic aerosols (up to 75% of $PM_{2.5}$) in Western Europe. Sea salts also had a significant influence (up to 29% of $PM_{10}$) in Atlantic and Mediterranean coastal regions.

Another approach to apportioning sources at regional scale uses receptor oriented methods focusing on the chemical composition of pollutants measured at a representative receptor site. Two intensive observation campaigns were conducted as part of the ChArMEx research program in Corsica (2013) and in Cyprus (2015). Statistical analysis of the chemical composition of both gaseous and particulate pollutants measured at Cap Corsica combined with the residence time analysis of air mass trajectories pointed to the contribution of anthropogenic sources located in regions characterized by intense anthropogenic activities (e.g. the Po valley and south-eastern France, both located in the north-western Mediterranean basin). In addition to primary (i.e. directly emitted) volatile organic compounds (VOCs) emitted by biogenic sources (BVOCs), a group of secondary pollutants composed of first-generation oxidation products of BVOCs was also identified, while another group was characterized by more oxidized VOCs (OVOCs) of both biogenic and anthropogenic origin. The combined analysis of VOC and aerosol compositions in $PM_1$ showed that during periods under a dominant biogenic influence, aerosol composition was dominated by the secondary organic fraction, whereas during periods of long range transport of anthropogenic emissions, the relative contributions of inorganic and organic fractions were the same. These results underline the importance of considering the roles of both anthropogenic and natural emissions in particulate pollution. The same approach is being applied using the observations acquired in Cyprus as representative of the eastern part of the Mediterranean basin.

# High atmospheric concentrations of aerosols, greenhouse gases and other pollutants



Evidence is growing for the deterioration of air quality over the Mediterranean basin. In this sub-chapter, we review the current situation over this semi-enclosed basin. We describe the spatio-temporal variabilities of the pollutants, greenhouse gases (GHGs) and aerosols, observed and modeled over the Mediterranean basin and how they help trace physical-chemical processes at regional and global scales through long-range transport. In a separate text box (see below), we focus in particular on secondary organic aerosols (SOA), a major component of fine particles, for which data and simulations were particularly scarce and uncertain especially over the western Mediterranean basin before ChArMEx. The Mediterranean basin is located in a transition zone between subtropical and mid-latitude climate regimes (Lionello, 2012), and is highly sensitive to climate change. In terms of sources of anthropogenic pollution, the basin is located at the intersection of three continents, Europe, Africa and Asia.

Satellites and models (e.g., Lelieveld et al. 2002; Nabat et al. 2013) together with campaigns such as the Mediterranean Intensive Oxidant Study (MINOS) (Ladstätter-Weissenmayer et al. 2003; Scheeren et al. 2003) show that, during the warm and dry Mediterranean summer season, air pollution above the Mediterranean often exceeds that observed over most parts of Europe. This is due to the convergence of European, African and Asian polluted air masses, to the absence of rain to clean up the atmosphere, and to the high insolation, which favors the formation of secondary pollutants like ultrafine particles or ozone. Natural aerosol pollution could originate from sources such as the African and Arabian deserts, active volcanoes, vegetation, or the sea surface. Pollutants, GHGs and aerosols originating from Asia can be trapped in the Asian monsoon and entrained to the upper troposphere before being redirected towards the eastern Mediterranean basin via the Asian monsoon anticyclone, where they accumulate and are subject to subsidence (Ricaud et al. 2014).

Continental sources including industrial and densely populated coastal areas (Kanakidou et al. 2011; Im and Kanakidou, 2012) or forest fires (Cristofanelli et al. 2013) affect the ozone ($O_3$) and carbon monoxide (CO) budgets with which methane emissions ($CH_4$) interplay through complex reactions with nitrogen oxides ($NO_x$) (Dentener et al. 2005), although the impacts of the respective source types are still not fully understood. Polluted air masses affecting the Mediterranean basin may originate from Europe (e.g., Pace et al. 2006), Asia (e.g., Lelieveld et al. 2002; Randel and Park, 2006), Africa (e.g. Ziv et al. 2004; Liu et al. 2009) and even North America (e.g., Formenti et al. 2002; Christoudias et al. 2012).

The transport and dispersion conditions of atmospheric pollutants over the western and eastern Mediterranean basin differ, as illustrated in Fig. 4, which shows the contrasted vertical air motion in the western and eastern parts of the basin in summer. The subsiding air aloft induced by the descending branch of the Hadley global circulation cell affecting the eastern basin, and the depth of the Persian Trough (an extension of the Indian monsoon), control the spatio-temporal distribution of the boundary layer (BL) height during summer. The resulting shallow mixed layer and weak zonal flow, leads to poor ventilation

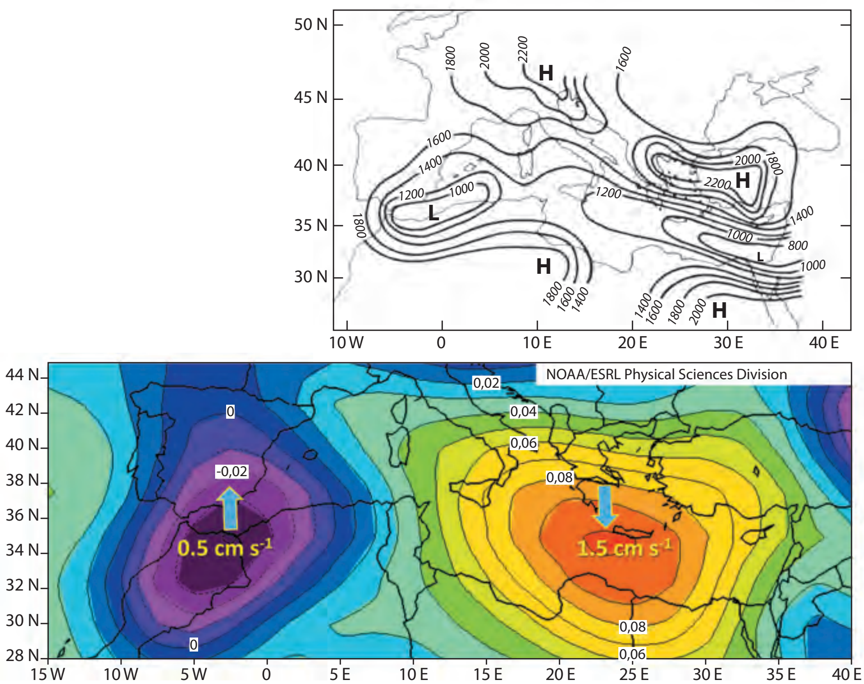


*Figure 4*

*Top panel: June to August 1948-2015 average of the NCEP/NCAR model omega (Pa $s^{-1}$) at 500 hPa (about 5.5 km altitude) showing a maximum downward air motion of about 1.5 cm $s^{-1}$ over Crete in the eastern Mediterranean, contributed by the descending branch of the African and Asian monsoon, and a maximum upward motion of about 0.5 cm $s^{-1}$ over the westernmost Mediterranean basin. Bottom panel: spatial distribution of the summer mixed layer height over the Mediterranean (from Dayan et al. 1996).*

rates, inhibiting the efficient dispersion of the pollutants. Several studies pointed to specific local (e.g. ventilation rates) and regional peculiarities (long-range transport) that enhance the building up of pollutant concentrations (Wanger et al. 2000; Matvev et al. 2002; Erel et al. 2007; Rudich et al. 2008; Drori et al. 2012) over the eastern Mediterranean basin.

Considering the long-range transport climatology that characterizes the Mediterranean basin, two different regimes can be observed: 1) From fall to spring with predominance in winter, and from the boundary layer to the upper troposphere, air masses mostly come from either Europe or the eastern Atlantic Ocean. 2) In summer, the origin of air masses affected by long-range transport over the eastern and western Mediterranean basin is distinct, more complex and altitude dependent. In the lower troposphere over the western basin, convective cells develop within the boundary layer with mostly air masses coming from Europe, northern Africa and eastern Atlantic Ocean. The coasts and mountains surrounding the western basin favor the development of mesoscale recirculations in summer that lead to the formation of ozone- and aerosol-rich layers above coastal areas and the sea (e.g. Millán et al. 2000). Over the eastern basin, the air masses originate from four major source regions: (i) west-north-west long fetch of maritime European air masses all year round, (ii) north-west flow originating in south-eastern Europe (etesian winds) in summer, (iii) south-east flow from the Arabian Peninsula in the fall, and (iv) south-west flow along the North African coast most frequent in late winter and spring (Dayan, 1986). In the mid-troposphere, whatever the season, air masses in both parts of the basin mainly come from the west. In summer, upper tropospheric air masses in the western basin mainly come from the west, but in the eastern basin, they also come from North Africa and the Arabian Peninsula (Ziv et al. 2004; Liu et al. 2009), and even farther away, from Asia (Lelieveld et al. 2002).

Several airborne campaigns have recently been conducted above the Mediterranean basin as part of the ChArMEx program: TRansport and Air QuAlity (TRAQA) in 2012, Aerosol Direct Radiative Impact on the regional climate in the MEDiterranean region (ADRIMED) and Secondary Aerosol Formation in the MEDiterranean (SAFMED) in 2013, and SAFMED+ and Gradient in Longitude of Atmospheric constituents in the Mediterranean basin (GLAM) in 2014. They addressed different processes that impact pollutants, GHGs and aerosols: air quality, radiative impact of aerosols, secondary aerosol formation, and long range transport. Combined with spaceborne and modeling studies, airborne *in situ* measurements highlighted the strong pollutant, GHG, and aerosol gradients between the western and eastern Mediterranean basin in summer from the mid-to-upper troposphere. Maxima in ozone, carbon monoxide, methane, nitrous oxide are commonly observed in the eastern basin, although on some occasions, minima in carbon dioxide are detected. The gradients were mainly attributed to the impact of long range transport of air masses originating either from Asia, North America, Europe, or Africa (Fig. 5). In the case of Asia, the Asian monsoon and its associated anticyclone are the main cause of the gradient by (1) trapping lower tropospheric pollutants and GHGs in the Asian monsoon; (2) updrafting pollutants and GHGs in the Asian monsoon up to the upper troposphere; (3) building up pollutants and GHGs within the Asian monsoon in the upper troposphere; (4) re-distribution of the pollutants and GHGs at a large scale by the Asian monsoon anticyclone to the Middle East and North Africa in the upper troposphere; and (5) subsiding pollutants and GHGs into the middle troposphere above the eastern basin (Ricaud et al. 2014). In the case of North America, biomass burning by long-lasting forest fires is the main source of aerosols, pollutants and GHGs. They are updrafted into the mid-to-upper troposphere by pyro-convection and/or through meteorological systems generally located in the Atlantic Ocean (warm conveyor pool, strong depression, etc.) following the jet stream towards the western Mediterranean basin (Ancellet et al. 2016; Ricaud et al. submitted). In the case of Africa, outbursts of Saharan desert dust are advected westward towards the Caribbean Sea, in the lower part of the troposphere, and, once in the central North Atlantic Ocean, are trapped within meteorological systems to be finally transported upward to the western Mediterranean basin like in the case of transport from North America.

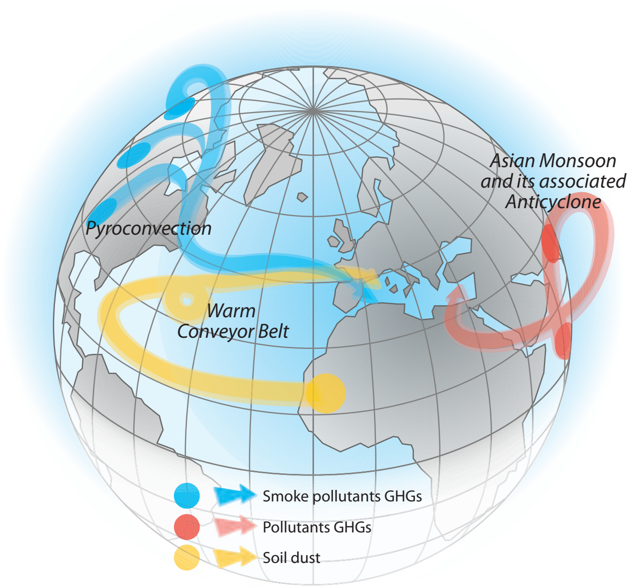


*Figure 5*
*Very long-range intercontinental transport of air masses over the Mediterranean basin. Dots identify source regions and arrows identify transport pathways.*

In addition to intercontinental transport of pollutants, GHGs and aerosols, the Mediterranean basin is a region that favors stratosphere-to-troposphere transport (Zbinden et al. in prep.). Stratospheric intrusions result in high ozone and low carbon monoxide or methane penetration into the troposphere. The depth, the irreversibility and the frequency of the stratospheric penetrations modify the tropospheric climatology and trends of these chemical species (Tyrlis et al. 2014).

Although measured and modeled data are still being analyzed in the ChArMEx program, their comparison underlines the difficulties models face representing 1) the significant fine structures observed both horizontally and vertically, 2) some processes that might be missing in the models (e.g. pyro-convection), 3) the mixing ratios of pollutants and GHGs with sufficient accuracy to estimate trends. Finally, chemical analyses that consist in assimilating satellite data with model data, widely used during the ChArMEx airborne campaigns, are efficient tools that benefit studies of the distribution and evolution of pollutants, GHGs, and aerosols over time.

The ChArMEx program allowed us to investigate the variabilities of pollutants, GHGs and aerosols in the Mediterranean basin in space and over time with particular emphasis on the summer period combining *in situ* airborne, spaceborne and model data, and to attribute these variabilities to several processes. Pyroconvection, convection, monsoon and the Asian monsoon anticyclone, the jet stream, etc., are dynamic processes that redistribute pollutants, GHGs and aerosols originating from desert dusts, biomass burning, etc., from Asia, Europe, Africa and North America over the Mediterranean basin. Some potentially key geographical areas that impact the eastern basin were revealed, e.g. the Arabian Sea, where future airborne campaigns may be deployed.



### Box 1
### The secondary organic aerosol (SOA)

The secondary organic aerosol (SOA) is made up of thousands of organic compounds originating from a wide range of natural and human sources (combustion of fossil fuel and biomass, gaseous emissions from the continental biosphere, marine emissions, etc.). SOA accounts for from 20% to 60% of very fine airborne particulate matter $PM_1$ (particles whose aerodynamic diameter is < 1 μm) (Zhang et al. 2007). This aerosol fraction is the most relevant for health issues (Pope and Dockery, 2006) but also climate effects. Organic aerosol particles scatter solar radiation, which cools the Earth's atmosphere, since part of the radiation is reflected back to space, but more recently their absorbing properties have also been put forward (Zhang X. et al. 2011). This affects the radiative properties of aerosol observed over the Mediterranean basin (Di Biagio et al. 2016). Depending on its hygroscopicity and mixing state, organic aerosols affect cloud micro-physics (Lohmann and Feichter, 2005; Zhu et al. 2016). SOA forms from semi-volatile organic compounds (SVOCs) by nucleation or condensation. Oxidative processes are most efficient in lowering the volatility of initially volatile compounds of anthropogenic and biogenic origin (Kroll et al. 2008). Anthropogenic emissions play a role in the formation of oxidants and hence in the formation of SOA, so that SOA of biogenic origin may be strongly reduced by reducing anthropogenic emissions, especially above large cities around the Mediterranean Sea (Sartelet et al. 2012). Research to elucidate the formation of SOA is still very active. Once formed, SOA can become highly viscous, which prevents later evaporation of the organic material (Virtanen et al. 2010).

During ChArMEx, and for the first time in the western Mediterranean, intensive and long-term aerosol mass spectrometer measurements filled the gap of missing observations of SOA over this region. On a yearly average, organic aerosol made up about 50% of $PM_1$ at Cape Corsica (POM in Fig.B1, left), among which around 90% were of secondary origin (LV-OOA and SV-OOA in Fig.B1, right). Surprisingly, aged (highly oxidized) SOA (LV-OOA) concentrations were found throughout the year, dominating OA even in winter when photochemical conditions are low. This result provides further evidence for the highly oxidative atmosphere of the Mediterranean. Additional isotopic $^{14}C$ measurements during the intensive campaign in the summer of 2013 showed that the majority of the organic aerosol was of biogenic origin (from the continental biosphere), although still 20% at Cape Corsica and 35% at Mallorca were of anthropogenic origin (fossil fuel combustion).

SOA modelling is still very challenging as the many chemical reaction pathways are not explicitly known and need to be parameterized in 3D models. Including a volatility basis-set (VBS) scheme including multi-step functionalization and fragmentation of organic compounds and formation of non-volatile SOA in the CHIMERE regional chemistry-transport model (Shrivastava et al. 2015) made it possible to retrieve the SOA mass and its fossil vs. biogenic fractions observed at surface stations at Cape Corsica and Mallorca (Cholakian et al. 2016), and recently in the Paris area (Zhang et al. 2015). Simulations with the Polyphemus model including the new multiphase SOAP organic aerosol scheme were in good agreement with measurements of concentrations of organic aerosol at Cape Corsica. The formation of extremely low-volatility organic aerosols has been added to the model to better represent organic aerosol properties (Chrit et al., 2016). Well evaluated chemistry-transport models is a prerequisite for simulating the regional scale interaction of SOA with climate (radiation, micro-physics) over the Mediterranean region as the next step. Ongoing developments will be constrained and validated by the large number of field observations made recently in the western Mediterranean as well as new measurements in the eastern basin as part of the ChArMEx program.

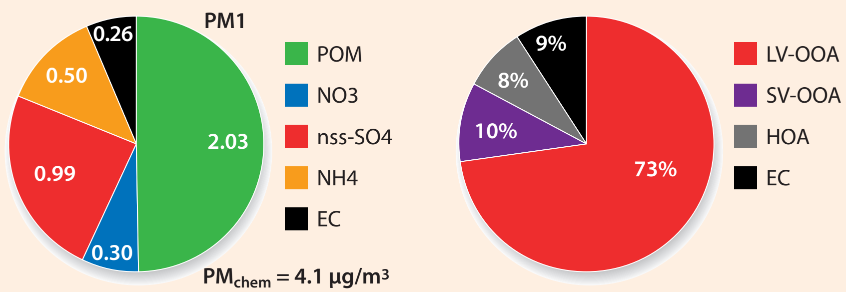


*Figure B1*

*$PM_1$ composition in µg $m^{-3}$ (left) and source apportionment (right) of carbonaceous aerosols at Ersa, Cape Corsica (42°58'N, 9°23'E, alt. 530 m), averaged over two years (from June 2012 to July 2014) from off-line filters and on-line aerosol mass spectrometer (Q-ACSM) measurements, respectively (after Nicolas, 2014). POM stands for particulate organic matter, NO3 for nitrate, nss-SO4 for non-sea salt sulfate, NH4 for ammonium end EC for elemental carbon. LV-OOA (low-volatility oxygen-like organic aerosol) is assimilated to aged secondary organic aerosol, SV-OOA (semi-volatile oxygen-like organic aerosol) to freshly formed secondary organic aerosol, HOA (hydrogen-like organic aerosol) to primary organic aerosol.*

# Atmospheric deposition to nutrient depleted seawater



Atmospheric deposition is the removal from the atmosphere of particles and gas by sedimentation (dry deposition) and by rainfall (wet deposition). Atmospheric inputs of pollutants and nutrients are of the same order of magnitude or larger than the riverine inputs for the Mediterranean region (Koçak et al. 2010; Christodoulaki et al. 2013; Moon et al. 2016), and hence of primary importance for marine ecosystems in the particularly oligotrophic seawater (i.e. with very low nitrogen and phosphorus nutrient concentrations) of the Mediterranean basin (Dugdale and Wilkerson, 1988). Indeed, owing to the small size (2.51 $10^6$ km²) of the Mediterranean Sea and to many intense land-based sources of emissions, open waters receive significant loads of nutrients through atmospheric deposition (Fig. 6). Some deposition events qualified as 'extreme events', such as dust inputs as high as 22 g $m^{-2}$ (Bonnet and Guieu, 2006), can occur at very short time scales (hours to days).

Atmospheric deposition is a significant source of major nutrients including inorganic (Kouvarakis et al. 2001) and organic nitrogen (Violaki et al. 2010), and phosphorous (Markaki et al. 2003). Even if water convection generally supplies most of the nitrogen (N) and phosphorus (P) available for biology in surface waters (where photosynthesis occurs) from deep waters, atmospheric inputs of inorganic N and P may be the most intense source of nutrients in summer when thermal stratification of the surface water column prevents vertical mixing (Pasqueron de Fommervault et al. 2015). Atmospheric deposition could also partly explain the increasing N:P ratio in the seawater column from the western

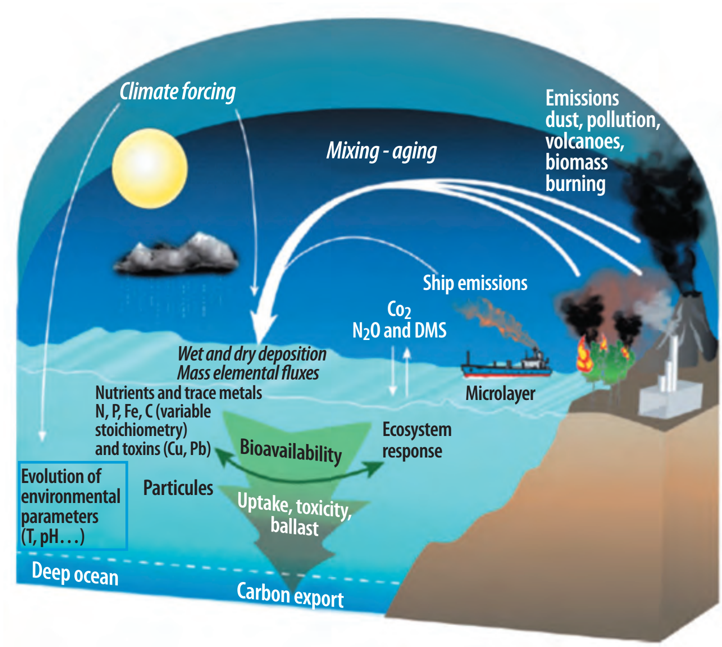


*Figure 6*
*Main processes occurring at the air-sea interface driven by different atmospheric inputs (adapted from LAW et al. 2013).*

to the eastern Mediterranean basin, since a similar N:P trend is observed in atmospheric deposition in these areas (MARKAKI et al. 2010). It has been shown that atmospheric deposition of iron (BONNET AND GUIEU, 2006) and trace metals (THEODOSI et al. 2010) represents significant inputs to support the primary production in surface waters. Deposition also transfers different atmospheric organic contaminants from the lower atmosphere to the ocean surface, including organochlorine compounds or polycyclic aromatic hydrocarbons (PAH), but their low deposition fluxes and their degradation in the water column limit their impact on marine ecosystems (CASTRO-JIMENEZ et al. 2012; BERROJALBIZ et al. 2014).

Deposited nutrients come from two main sources: anthropogenic sources and soil dust, the latter mainly from the Sahara but also from the Middle East in the easternmost Mediterranean basin. Anthropogenic inputs control the deposition flux of N, inorganic nitrogen being mainly supplied by dry deposition (MARKAKI et al. 2010), and organic nitrogen by wet deposition (VIOLAKI et al. 2010). The deposition of desert dust plays an important role in the fluxes of P and trace metals due to sporadic but intense deposition events (ÖZSOY AND ÖRNEKTEKIN, 2009; GUIEU et al. 2010; MORALES-BAQUERO AND PEREZ-MARTINEZ, 2016), even if the contribution of anthropogenic aerosol deposition is significant (between 10% for Fe to 90% for Zn; GUIEU et al. 2010). Dust deposition releases dissolved inorganic phosphorous (DIP) and nitrate in N- and P-depleted surface waters (RIDAME et al. 2014). The atmospheric deposition of mineral dust also determines enrichment of the sea-surface microlayer in dissolved trace metal micro-nutrients such as Cd, Co, Cu, Fe (Tovar Sanchez et al. 2014). However, it has been shown that dust deposition can result either in a net release or in scavenging of DIP and nitrate (Louis et al. 2015) and trace elements (Wagener et al. 2010; Wuttig et al. 2013) in seawater, depending on the quantity and quality of *in situ* dissolved organic matter at the time of the deposition. Indeed, the dissolved organic matter can control the dissolution of nutrients carried by dust particles.

Recent experiments in realistic conditions showed that, by providing P and N to the marine biosphere, wet Saharan dust deposition strongly stimulates primary production and phytoplankton biomass for several days after deposition (Ridame et al. 2014; Guieu et al. 2014b; Fig. 7). From such studies, the inputs of atmospheric trace metals into the Mediterranean Sea associated with dust deposition are also suspected of stimulating bacteria and phytoplankton species such as cyanobacteria that are able to assimilate atmospheric dinitrogen $N_2$ (Ridame et al. 2011). The extent of the fertilizing effect of dust deposition events in the Mediterranean was revealed by statistically positive correlations between dust deposition and surface chlorophyll concentrations in combined remote sensing and modeling approaches (Gallisai et al. 2014). However, a negative effect of atmospheric deposition on chlorophyll was observed in the regions under the influence of aerosols of European origin (Gallisai et al. 2014). Indeed, inputs of anthropogenic aerosols, such as Cu-rich aerosol, are suspected of inhibiting phytoplankton growth (Jordi et al. 2012). Dust deposition has also been shown to modify the structure of the bacterial community by selectively stimulating and inhibiting certain types (Pulido-Villena et al. 2014). By stimulating predominantly heterotrophic bacteria (i.e. that use organic carbon for their growth), atmospheric dust deposition can increase the recycling of carbon, thereby reducing net atmospheric $CO_2$ drawdown and the fraction of dissolved organic carbon that can be mixed and exported to deep waters (Pulido-Villena et al. 2008). In contrast, Saharan dust deposition in the Mediterranean can enhance the export of particulate organic carbon to the deep ocean by acting as ballast and facilitating aggregation processes (i.e. Bressac et al. 2014; Desboeufs et al. 2014).

To tackle these questions at the scale of the Mediterranean basin, numerical models need to be developed. The main challenges are to quantify the relative contributions of anthropogenic and natural deposition of nutrients and contaminants in this region in a context of Mediterranean climate change, and to improve our ability to simulate the chemical elements and their soluble fraction in 3-D atmospheric transport and chemistry models. Modeling the size distribution of desert dust particles and its evolution from emission to deposition contributes to the difficulty. *In situ* measurements by aircraft suggest a coarse mode of large soil dust particles over the Mediterranean (with a volume mean effective diameter in the range of 3.8-14.2 μm) as large as that observed close to the Saharan and Sahelian source regions (Denjean et al. 2016). Balloon-borne aerosol counters have also shown the frequent presence of large particles (> 20 μm) inside airborne desert dust plumes over the western Mediterranean (Renard et al. 2016). These particles, which appear to be transported for several days without significant gravitational sedimentation, in contradiction to their size, probably control the mass flux of deposition of dust.

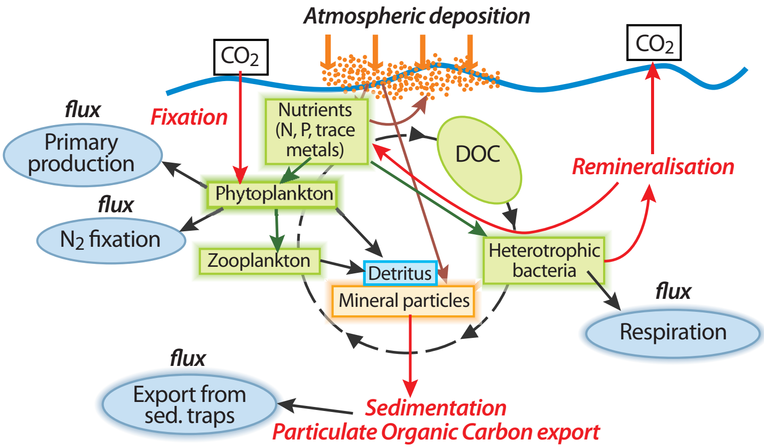


*Figure 7*
*Stocks (green) and fluxes (blue) measured during mesocosm experiments after the simulation of a realistic atmospheric input in a water body large enough to be representative of natural processes (Guieu et al. 2014b; modified from de Leeuw et al. 2014).*

Predicting inputs of atmospheric nutrients in the future is important to understand the vulnerability of the marine ecosystem and carbon fluxes. Climate change simulations predict a hotter dryer climate in the Mediterranean basin (e.g., Hertig & Jacobeit, 2008), a situation that could increase dust emissions and transport due to increased aridity (Moulin & Chiapello, 2006) but also intense deposition events (Beaulant et al. 2011). However, the most recent measurements of dust deposition in Corsica (2011-2013) show that deposition fluxes are much lower than in the three past decades shown by existing records in the area (11-14 g $m^{-2}$ $yr^{-1}$) (Vincent et al. 2016). But it is not yet understood if the reduction in dust deposition is related to a decrease in the frequency of dust events and/or to a change in deposition processes and patterns in the Mediterranean region. The temporal dynamics of marine N and P concentrations since 1985 showed high sensitivity to anthropogenic atmospheric deposition and are expected to decline in the coming decades due to mitigation/control of pollutant emissions (Moon et al. 2016). In the same way, Christodoulaki et al. (2016) showed that even if the human-driven atmospheric deposition of N and P has led to a 16% increase in total phytoplankton biomass over the past one and a half centuries, small changes in carbon fluxes and planktonic biomasses are predicted for the near future with the projected inputs of N and P. The regulation of inputs of anthropogenic nutrients could be a key driver of seawater nutrient cycles and hence marine ecosystems in the future. However, findings concerning the sources of the atmospheric trace metals and effects need to be completed to enable high quality projections in a context of future changes.

# Impact of atmospheric chemistry on the regional climate



In this section, we address the complex atmospheric-chemistry and climate interactions and feedback processes in the Mediterranean region.

## Processes

Projecting climate changes at regional scale remains a challenge. This is especially true in regions where aerosols play a significant role in the radiative balance with effects on the climate and water cycle (Nabat et al. 2014 and 2015) like in the Mediterranean region. Regional projections of this type are required for the design of adaptation and mitigation strategies and a deeper understanding of regional processes is thus needed.

Atmospheric aerosol particles play a major role in the water cycle and also in the Earth's energy balance through their radiative effects, including direct effects (by extinction of radiation and attenuation of surface illumination), semi-direct effects (due to the heating of turbid air layers by particles absorbing solar radiation), and indirect effects (through their influence on cloud properties). The uncertainty of these climate effects exceeds that of any other forcing because the physical, chemical and optical properties of aerosols are highly variable in space and time since their atmospheric lifetime is short and their emissions are very heterogeneous (Forster et al. 2007).

The Mediterranean region is at the intersection of large scale circulation patterns with highly contrasted sources of particles. The region is subject to high particle loading as described in the sub-chapter 'High concentrations of aerosols and pollutant and greenhouse gases', high photochemical activity, with mixing of different origins: particles come from anthropogenic sources such as highly densified cities in Europe, Turkey, and the Middle East; desert dust from the Sahara and from the Middle East in the eastern part of the basin (Mamouri & Ansmann, 2015); maritime particles from the Mediterranean Sea; as well as organic particles from biomass burning (Lelieveld et al. 2002; Sciare et al. 2003, 2008). Expected impacts of climate change in the region include heat stress associated with poor air quality in the urban environment (Lelieveld et al. 2012, 2015). This is why the impact of particles in the Mediterranean region is high and is expected to change, and why each effect of different particles on the climate of the Mediterranean region, whether direct or indirect, needs to be understood and quantified.



## Assessment of aerosol direct radiative forcing (DRF)

Aerosols observed over the Mediterranean basin are known to be able to interact with both shortwave (SW) and longwave (LW) radiation (Nabat et al. 2012; Papadimas et al. 2012; Zanis et al. 2012; Sicard et al. 2014). In the SW spectral range, due to their variability in size and in chemical properties, they can scatter (sea salt, sulfates, nitrates, ammonium and secondary organic particles) or scatter plus absorb (black and brown carbon from combustion [smoke], certain types of mineral dust) solar radiation. Only mineral dust and sea salt can interact with LW radiation due to their large particle size. Consequently, Mediterranean aerosols significantly affect the radiative budget of the Mediterranean by (1) decreasing surface incoming shortwave radiation, (2) increasing/decreasing outgoing shortwave fluxes depending on the surface albedo, and (3) possibly by heating turbid atmospheric layers when the particles absorb solar light.

Concerning pollution aerosols, SW direct shortwave radiative forcing (DRF) has been estimated at the local scale by many authors (Horvath et al. 2002; Markowicz et al. 2002; Meloni et al. 2003; Roger et al. 2006; di Sarra et al. 2008; Di Biagio et al. 2009, 2010). These authors showed a significant decrease in surface solar fluxes of 20–30 W $m^{-2}$ (daily mean) at different locations including Almeria (Spain), Finokalia (Greece), Lampedusa (Italy), Marseilles and Toulon (France). In parallel, the combination of surface and satellite remote-sensing observations performed at Lampedusa has been used to calculate the radiative effects, in both the shortwave (Di Biagio et al. 2010) and longwave (di Sarra et al. 2011; Meloni et al. 2015) spectral ranges for different cases of Saharan dust intrusions. These studies emphasized that desert dust in the LW spectral range has a significant radiative effect, and offsets a large fraction of SW forcing (di Sarra et al. 2011; Meloni et al. 2015). More recently, based on remote-sensing observations in Barcelona and 1-D radiative transfer calculations, Sicard et al. (2014) also estimated the LW radiative effect of dust. Only a few studies are available concerning the radiative impact over the Mediterranean region of intense biomass burning events. One estimate was proposed by Formenti et al. (2002) for an aged Canadian biomass-burning plume and revealed a significant SW surface dimming of 60 W m$^{-2}$. In addition, the radiative effect induced by smoke aerosols at Lampedusa between August 3 and 23, 2003, during an exceptionally hot and dry season when the Mediterranean atmosphere was affected by massive forest fires, was estimated by Pace et al. (2005) to be between +22 and +26 W m$^{-2}$. For a complete review of local direct radiative forcing see Mallet et al. (2016).

At the regional scale, Papadimas et al. (2012) proposed an estimation of the aerosol DRF using MODIS data from 2000 to 2007 for both all-sky and clear-sky only conditions. These authors derived a multi-year regional mean surface DRF of -19 W m$^{-2}$, associated with a DRF of -4.5 W m$^{-2}$ at the top of the atmosphere (TOA). It should be noted that such radiative forcing is regionally higher than that exerted by greenhouse gases. Regional modelling studies were also recently conducted by Nabat et al. (2012, 2015) using the coupled-chemistry RegCM and the CNRM-Regional Climate System Model (RCSM) models for multi-year simulations. These authors reported a mean SW regional surface (TOA) DRF of -13.6 W m$^{-2}$ (-5.5 W m$^{-2}$) and -20.9 W m$^{-2}$ (-10.5 W m$^{-2}$) for the RegCM and CNRM-RCSM (see Fig. 8) models, respectively. Zanis et al. (2012) also proposed a regional estimate of the DRF of anthropogenic particles for the 1996-2007 period using RegCM and showed a significant negative forcing of up to -23 W m$^{-2}$ at TOA over Eastern Europe.

In parallel with the radiative forcing exerted by aerosols, Richards et al. (2013) investigated the effect of reducing certain sources of emissions on the radiative effect of ozone over the Mediterranean (ozone shows a marked but localized summertime maximum, especially over the eastern basin). These authors reported a mean radiative effect at the top of the atmosphere of between -1 and -40 W m$^{-2}$, depending on the types of emission tested. Hauglustaine & Brasseur (2001) reported mean radiative forcing associated with an increase in tropospheric ozone since the preindustrial era of around 0.70 W m$^{-2}$. Such studies demonstrate that the radiative effect of ozone is significantly lower than that exerted by natural/anthropogenic aerosols over the Mediterranean region.

The aerosol atmospheric load can also directly impact the production of secondary gaseous species (i.e. chemically produced from primary emitted species) by attenuating or scattering visible and UV radiation. Recently, Mailler et al. (2016) showed a net reduction in the photolysis rates of ozone and nitrogen oxides due to the absorbing effect of a mineral dust plume observed in Lampedusa. This effect led to a change of several ppbs in ozone surface concentrations. Over the Mediterranean Sea and continental Europe, close to the sources of $NO_x$, the effect of dust leads to reduced ozone concentrations (but an increase occurs over remote areas such as the Sahara and the tropical Atlantic Ocean). By reducing photosynthetically active radiation (PAR), the aerosol may also reduce crop production, and hence biogenic emissions, leading to complex interactions in the formation of secondary organic aerosols that are not yet well understood.



## Implication of aerosol direct radiative forcing (DRF) in the Mediterranean water cycle

Concerning surface and TOA atmospheric forcings, Zanis et al. 2012; Spyrou et al. 2013; Nabat et al. 2014, 2015a,b recently investigated how changes in the radiative budget due to natural/anthropogenic aerosols influence the surface temperature (over both land and sea), relative humidity profiles, exchanges (latent heat fluxes) between ocean and atmosphere, cloud cover (semi-direct effect of absorbing particles), precipitation, and finally the whole Mediterranean hydrological cycle. Indeed, notable perturbations in sea surface-atmosphere fluxes are expected despite the relatively small size of the Mediterranean Sea, since the latter plays an important role at a much larger scale by providing moisture for precipitation to its surrounding land areas, which extend to northern Europe and northern Africa (Gimeno et al. 2010 and Schicker et al. 2010). In parallel, the absorbing particles over the Mediterranean Sea (Mallet et al. 2013) could have a semi-direct effect that could modify the vertical profiles of relative humidity and cloud cover.

In that context, using simulation ensembles of the direct radiative effect of aerosols (Fig. 8a) carried out with the regional climate system model CNRM-RCSM, Nabat et al. (2015) showed annual average cooling of the Mediterranean sea surface caused by aerosols of -0.5 °C, up to -1 °C locally, and higher in spring and summer when aerosol loads (mainly sulfate and dust particles) are maximal (see summer average in Fig. 8b). This cooling also affects the surrounding land, not only due to negative aerosol DRF over land, but also because of the advection of maritime cooler air over land regions. For example, in summer, northern winds over the eastern basin favor additional cooling over northern Libya and Egypt.

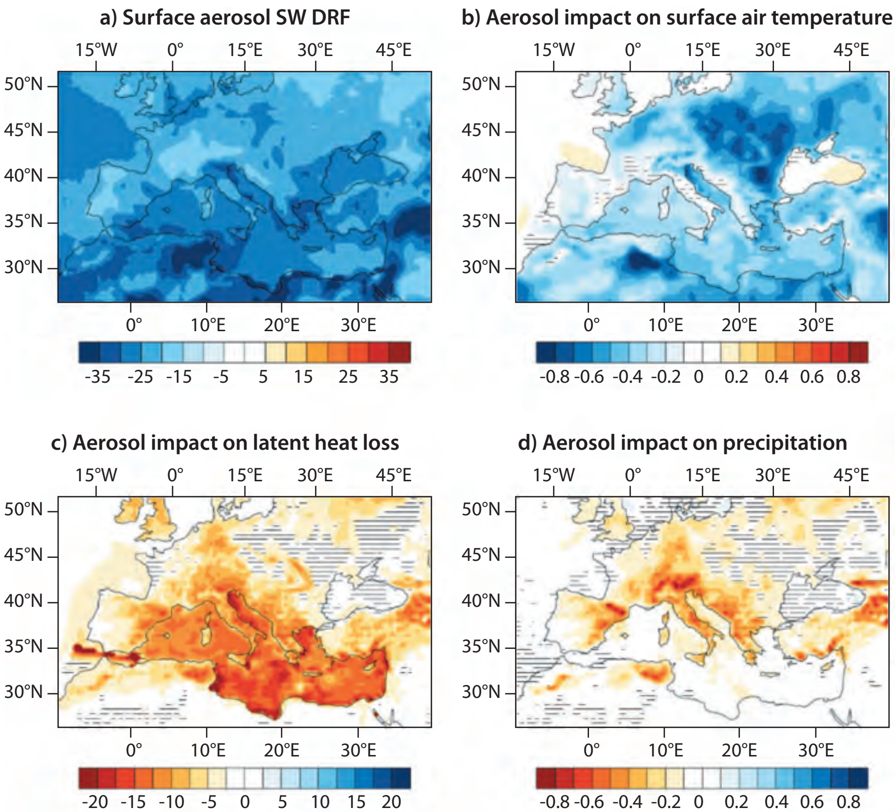


*Figure 8*
*Average (JJA 2003-2009) surface aerosol direct radiative forcing (DRF, W $m^{-2}$) (a) and the resulting impact of the aerosol on surface air temperature (°C) (b), latent heat loss (W $m^{-2}$) (c) and precipitation (mm $day^{-1}$) (d), simulated by the CNRM-RCSM regional model. Hatched areas are not significant at the 0.05 probability level.*

In addition, aerosols are responsible for a decrease in the latent heat loss by evaporation over the Mediterranean Sea (Fig. 8c) due to these lower sea surface temperatures (SST). Consequently a reduction in the whole hydrological cycle has been attributed to aerosols, resulting in an average 10% decrease in specific humidity in the lower troposphere, in cloud cover and in precipitation (Fig. 8d). In addition, dust aerosols also reduce atmospheric convection in the region by warming the lower troposphere by absorbing solar radiation, and hence stabilizing the atmosphere. The comparison of these results with the model response in atmosphere-only simulations shows that feedback is reduced if SST cannot be modified by aerosols, highlighting the essential role of the Mediterranean SST and the need to use atmosphere-ocean coupled regional models in regional aerosol-climate studies. In addition, the decrease in SST causes an increase in the density of surface Mediterranean waters that favors ocean convection in sub-basins where deep water masses are formed (Gulf of Lion, Adriatic Sea and Aegean Sea), and reinforces the Mediterranean thermohaline circulation.

It is also worth mentioning that since the 1980s, aerosol loads have been dramatically reduced over the Mediterranean basin (NABAT et al., 2013), because of the reduction in anthropogenic emissions of sulfate precursors in Europe (improved air quality standards plus economic crises). As a consequence, aerosol DRF decreased over the region between 1980 and 2012, leading to an increase in surface solar radiation (brightening period) and additional warming of land and ocean surface temperature: aerosol changes explain 23% of the warming in the region over this period (NABAT et al., 2014).



## Aerosol-cloud interactions and impact on precipitation

The Mediterranean region is particularly vulnerable to climate change due to its location at the interface of the hot dry North African climate and the cooler wetter European climate. The water cycle in this region is very sensitive to the position of the descending branch of the Hadley cell, which is expected to move poleward following global warming, leading to increasingly scarce fresh water (GIORGI & LIONELLO, 2008). Understanding the formation of clouds and precipitation and its link with atmospheric composition is particularly important in this region. Clouds and precipitation strongly influence tropospheric composition and radiative properties, water transport and energy redistribution. At the cloud scale, clouds and the precipitation life cycle are controlled by the prevailing meteorology and aerosol particles, particularly the presence of cloud condensation and ice nuclei (CCN/IN) (FLOSSMANN WOBROCK, 2010). Indeed, hydrometeors cannot form spontaneously in the thermodynamic conditions encountered in the atmosphere. They need a substrate (a nucleus) during the early stage of formation. An aerosol particle that serves as a nucleus for a cloud droplet is called a cloud condensation nucleus (CCN), and for an ice crystal, an ice nucleus (IN).

An additional consequence of the enlargement of the Hadley cell (ICCP, 2014b) is the increasing frequency of dust particles transported over the eastern Mediterranean. ROSENFELD et al. (2001) reported that an excess concentration of atmospheric dust can prevent cloud precipitation. This argument is often referred to as the second indirect effect in the Twomey classification (1980): an excess of CCN causes an increase in the number of droplets and consequently the cloud droplet size distribution shifts to smaller sizes, thereby narrowing the droplet size distribution. This hampers precipitation. Indeed, precipitation is triggered by a mechanism that forms hydrometeors of millimetric sizes in a matter of minutes. Only the presence of a few large hydrometeors in the population that will fall and collect the population of small hydrometeors can lead to precipitation. The narrowing of the size distribution eliminates the largest hydrometeors and reduces precipitation ability. This will inherently amplify dryness due to extension of the Hadley cell, and is referred as the "desertification positive feedback loop".

Our understanding of the processes that take place inside clouds has considerably increased in recent decades (Flossmann and Wobrock, 2010, Lohmann et al. 2010, Levin and Cotton, 2008). Microphysical features of clouds in the Mediterranean region have already been characterized together with their link with the loading of aerosol particles (Levin et al. 1996, 2005; Rosenfeld et al. 2001; Teller et al. 2012). The impact of aerosols is uncertain but potentially maximal when aerosol particles can cause the formation of ice crystals in clouds. This is referred to as the ice indirect effect by Lohmann (2002). Indeed, global precipitation is predominantly produced by clouds containing ice crystals (DeMott et al. 2011). Aerosols that can act as IN are mostly insoluble particles that often mimic ice lattice structure. Only a few types of aerosols have this property, including mineral dust, volcanic ash, and bioaerosols such as bacteria, fungal spores, and pollen (Vali, 1985; Hoose & Möhler, 2012). Their IN ability, their likelihood of precipitating the ice phase, and to what extent anthropogenic aerosols can play a role in cloud ice formation are still not fully understood although the number of laboratory studies on the IN properties of different kinds of aerosol particles has been continuously increasing (e.g., Möhler et al. 2007, for bacteria; Connolly et al. 2009, and Ardon-Dryer & Levin, 2014, for dust).

Even though air quality and water resources in the Mediterranean region have been the center of scientific interest, and have been studied intensively, many questions remain unanswered, in particular in the eastern part i.e., how and to what extent natural and anthropogenic aerosols can increase or prevent rainfall (e.g. Levin et al. 1996, Teller & Levin, 2006).

# Ongoing research and recommendations

Recent studies clearly demonstrated the added value of using regional climate models including ocean-atmosphere coupling to study the impact of the aerosol direct radiative effect on the Mediterranean climate. One priority should now be to conduct an intercomparison of such models to check the robustness of individual models, as scheduled in the next phase of the MedCORDEX program (https://www.medcordex.eu/). In addition, the impact of the anthropogenic and natural aerosol DRF on future climate needs to be investigated using different RCP scenarios, with the 8.5 scenario as a priority. The second important point concerns the role of aerosols in cloud microphysical and macro-physical properties at climatic scale. To this end, regional climate simulations should be built including the first (aerosol-cloud albedo) and second (aerosol-cloud precipitation) indirect effects of anthropogenic and natural aerosols on warm clouds. A better representation of dust-IN interactions is also required over this region especially for the eastern Mediterranean. Specific experimental campaigns focused on this aspect associated with improvements in its representation in climate models should be encouraged.

# Impacts of air quality on health



There is growing concern about the detrimental effects of air pollution on human health (WHO, 2013). However, data have only been collected in some countries in the Mediterranean region (WHO, 2014). A recent review systemically and qualitatively screened relevant papers and reports published between 2000 and 2014 on health impact of air pollution in the eastern Mediterranean region. The authors found only 36 published studies. A variety of indoor and outdoor exposures associated with various acute and chronic respiratory health outcomes were included. However, data were limited to a few studies in a few eastern Mediterranean countries and concerned both indoor and outdoor air pollution (Abdo et al. 2016). Several adverse respiratory health outcomes were positively associated with various indoor/outdoor air pollutants throughout the region. Respiratory health outcomes ranged in severity, from allergies and general respiratory complaints to lung cancer and mortality. In addition, although Mediterranean countries are highly exposed to dust storms and wildfires, their effects have rarely been studied. In this section, we present recent data on the consequences of exposure to particulate air pollution and related health impacts in the case of both anthropogenic and natural air pollution collected in the Mediterranean region. These include air pollution reduction scenarios.

## Impact of air pollution on health in Bejaia (Algeria)

In Algeria, monitoring of air pollution is limited to three big cities (Algiers, Annaba and Oran), and little is known about the impact of air pollution on health in most of the country. *Ad hoc* measurements of ambient concentrations of particulate matter taken in the Bejaia region in July 2015 indicated that the annual average $PM_{10}$ (particulate mass concentration of particles smaller than 10 µm in diameter) and $PM_{2.5}$ (*idem* for particles smaller than 2.5 µm in diameter) levels in this urban zone exceed the World Health Organization (WHO) air quality guideline (AQG) values, the EU AQG and Algerian AQG. As expected, the highest 24-hr average concentrations ($PM_{10}$= 103.7 ±15.1 µg $m^{-3}$ and $PM_{2.5}$= 35.7 ±9.5 µg $m^{-3}$) were measured during peak traffic flow hours, pointing to a significant contribution of emissions from vehicles, which are generally old. These assessments of air pollution put forward that an estimated 55 deaths per year could be avoided by reducing the annual $PM_{10}$ levels to the WHO AQG of 20 µg $m^{-3}$. Furthermore, not exceeding the $PM_{10}$ WHO AQG would reduce respiratory and cardiac hospital admissions by 36 per 100,000 and 23 per 100,000, respectively (Benaissa et al. 2016). The same author previously showed that people who live in areas with high traffic density and high air pollution suffer from higher rates of asthma and COPD morbidity and mortality (Benaissa et al. 2014).

## Impact of air pollution on health in Beirut (Lebanon)

Another study was conducted in Beirut in 2012 where the main sources of pollution are vehicles and dust storms as there is no industrial activity in the vicinity. Results (Farah et al. 2104; Farah et al. 2016) showed that the annual average concentrations of $PM_{10}$ and $PM_{2.5}$ exceeded the annual average of WHO AQG (20 and 10 µg $m^{-3}$, respectively) by 150% and 200%, respectively. The mean $PM_{2.5}$:$PM_{10}$ ratio for the entire study period was 0.61 ±0.12, indicating that in Beirut about 61% of $PM_{10}$ is made up of $PM_{2.5}$, i.e. that particulate air pollution is dominated by fine particles. The highest daily averages of $PM_{10}$ and $PM_{2.5}$ were measured in spring and summer (March to July) (Fig. 9), echoing the higher frequency of dust storms in this part of the Mediterranean at that period of the year. The correlation between particulate matter and nitrogen dioxide ($NO_2$) indicated that vehicle exhaust emissions contribute an average of 93% of $PM_{2.5}$ and 43% of $PM_{10}$.

Using data collected daily in 2012, the BAPHE (Beirut Air Pollution and Health Effects) study showed that total respiratory admissions were significantly associated with the same day (lag=0) level of $PM_{10}$ (1.2% increase per 10 µg $m^{-3}$ rise in daily mean pollutant concentration) and $PM_{2.5}$ (1.6 % per 10 µg $m^{-3}$ rise in daily mean pollutant concentration) and that children and the elderly were at higher risk (Mrad Naklé et al. 2015). The results obtained in Beirut are similar to, and consistent with, those obtained in other international studies. Air pollution control is expected to reduce the number of disease admissions in Lebanon.

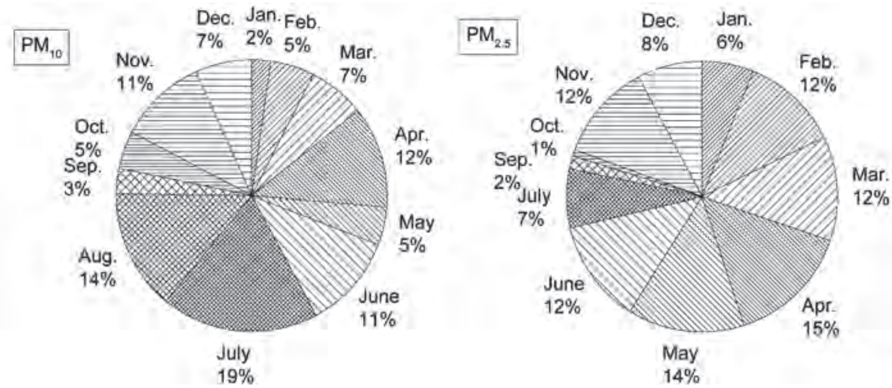


*Figure 9*
*Relative distribution of WHO AQG exceedance days for $PM_{10}$ and $PM_{2.5}$ during the different months of the study in Beirut (from FARAH et al. 2016).*

# Impacts of natural particles in the Mediterranean on health

Since climate change will accelerate desertification processes in arid and semi-arid regions, desert dust outbreaks and wildfires will increase substantially in both frequency and intensity in the near future in various regions of the world including the Mediterranean. The recent MED-PARTICLES ("Particles size and composition in Mediterranean countries: geographical variability and short-term health effects"; http://95.110.213.190/medparticles/) project studied the impact of dust storms and wildfires on human health in 13 cities of Euro-Mediterranean countries, including several on the Mediterranean coasts (Fig. 10): Barcelona and Madrid (Spain), Marseille (France), Bologna, Milan, Modena, Palermo, Parma, Reggio Emilia, Rome, and Turin (Italy), Athens and Thessaloniki (Greece). African dust outbreaks were highly frequent in southern sites during the period 2001-2011, i.e. occurred on 30% to 37% of the days, whereas they occurred on less than 20% of the days at northern sites (STAFOGGIA et al. 2016). The study also identified Saharan dust outbreaks as the largest source of $PM_{10}$ in regional background southern sites of the Mediterranean (35% to 50% of $PM_{10}$), with seasonal peak contributions to $PM_{10}$ of up to 80% of the total mass. Significant increases by 10-µg $m^{-3}$ in non-desert and desert $PM_{10}$ were associated with a lag of 0-1 day with increases in natural (non-accidental) total and cardio-respiratory mortality and hospital admissions (STAFOGGIA et al. 2016). The occurrence of wildfires assessed by satellite observations was also linked with health by the MED-PARTICLES project. A significant increase in natural and cause-specific mortality was observed on smoky days, with the biggest increase in mortality from cardiovascular diseases (FAUSTINI *et al.* 2015). $PM_{10}$ had more marked effects on cardiovascular and respiratory mortality on smoky days than on other days, suggesting particulate matter is an effective component of fire smoke. This new evidence for adverse health effects of natural sources reinforces the need for control of anthropogenic sources, especially on days when natural dust levels are high, to avoid individuals being subject to excessive exposure resulting from the accumulation of anthropogenic and natural air pollution.


*Figure 10*
*Urban cities involved in the MED-PARTICLES ("Particles size and composition in Mediterranean countries: geographical variability and short-term health effects") project.*

# Reducing air pollution in the Mediterranean region

Recent data from the Mediterranean region showed that reducing air pollution is beneficial (Benaissa et al. 2016). According to the VIIAS (Integrated Assessment of the Impact of Air Pollution on the Environment and Health) project (www.viias.it), 34,600 and 23,400 are the mean numbers of annual premature deaths in Italy that can be attributed to $PM_{2.5}$ and $NO_2$, respectively (http://www.viias.it/sites/default/files/ancona.pdf). Applying the 2020 Italian National Energy Strategy (NES) would prevent 17% of the $PM_{2.5}$-, and 57% of the $NO_2$-attributable deaths. However, compliance with the EU Directive for $PM_{2.5}$ would have an even higher impact with a 22% annual reduction in attributable mortality, with the highest reduction (-30%) in urban areas. For

$NO_2$, compliance with the EU Directive would result in a 25% annual reduction in attributable mortality, especially in urban areas (-31%). Like for ozone, VIIAS estimated 1,710 annual premature deaths from respiratory diseases due to long-term exposure, and 2,230 annual premature deaths from non-accidental causes due to short-term exposure. Applying the 2020 Italian NES would prevent 23% of the long term and 14% of the short term $O_3$ attributable deaths, especially in the south (-26% and -20%, respectively) and in rural areas (-27% and -21%, respectively).



## Recommendations

Studies on the impact of air quality on health conducted in the Mediterranean region underline the need to improve assessment of exposure and estimations of anthropogenic and natural (especially dust storms and wildfires) related health outcomes in countries where they have been neglected. A better understanding of the role played by meteorology in the direction and the extension of dust events in space and over time is also important. Prevention needs to be promoted, since it has been shown to be effective in reducing effects on health.

Sub-chapter 1.4.6

# The (uncertain) future of air quality



Assessing the future evolution of air quality requires taking climate projections into account and designing environmental policies. In the context of adaptation to climate change, the geophysical changes expected in coming decades will have an impact on chronic and extreme air pollution events (Jacob and Winner, 2009). But air quality is also sensitive to climate mitigation strategies: the social and technological changes required to reduce greenhouse gas emissions will be accompanied by changes in the emission of air pollutants and of their precursors. There are potentially large co-benefits between air quality and climate change mitigation that could help efforts to identify win-win strategies. Nevertheless, mitigating climate change can also cause collateral damage to air quality. It is thus very important to identify the co-benefits and possible collateral damage to maximize the former while minimizing the latter. Here we briefly review recent results on the impacts of climate change on air quality in the Mediterranean region in terms of ozone and particles, and describe the positive and negative feedback of climate change on air quality.

## Adaptation: the impact of climate change on air quality

### Surface ozone

Ozone concentrations in the troposphere are driven by many chemical and dynamic processes including emissions of ozone precursors and meteorological variables. Climate change has an impact on the tropospheric ozone through its effects on biogenic emissions of ozone precursors (mainly volatile organic compounds - VOCs), meteorological parameters (temperature, precipitation, humidity) and atmospheric chemistry (chemical budget, photochemical regimes). Climate change will be accompanied by a reduction in rainfall over southern Europe, creating wintertime deficits that reduce soil water content, thereby further increasing average temperatures and the frequency and severity of heat waves (Fiore et al. 2012; Vautard et al. 2013) with major consequences for summertime ozone pollution in Europe and the Mediterranean, which have already been pointed out (Langner et al. 2005; Meleux et al. 2007). A meta-analysis of the 25 projections of ozone pollution in Europe in the context of climate change published between 2007 and 2015 was conducted by Colette et al. (2015a) to explore the robustness of the projected impact of climate change on surface ozone (Fig. 11). The corresponding climate ozone penalty is defined as the incremental change in ozone that can be attributed to climate change alone, in the absence of changes in anthropogenic emissions of ozone or other drivers. The penalty was confirmed over most of continental Europe, especially in European countries located on the Mediterranean rim where such a penalty is robust, i.e. consistent in over two-thirds of the models in the ensemble (diamond symbols in Fig. 11).

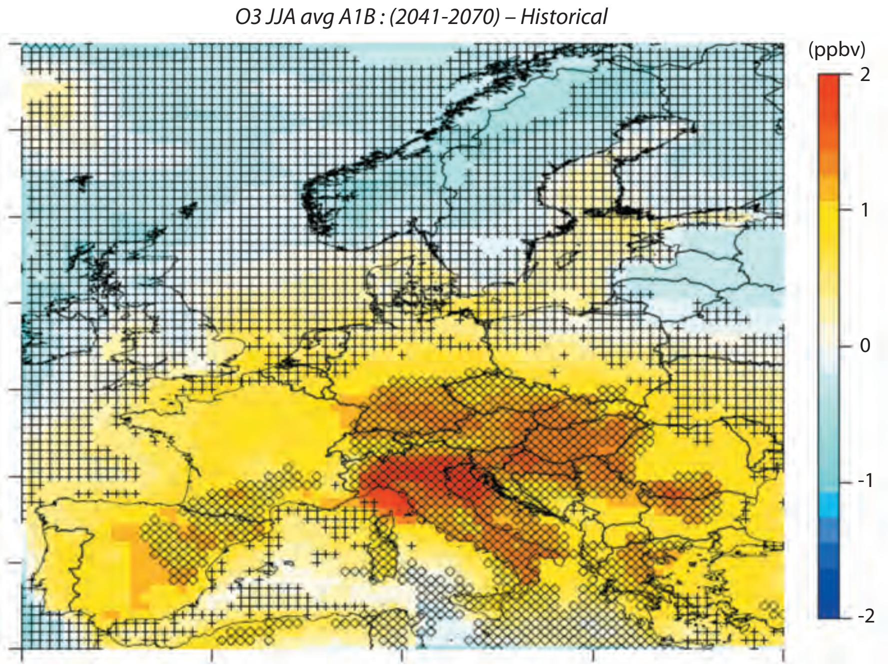


*Figure 11*
*Increase in surface summertime ozone concentrations (ppbv) by the middle of the 21st century in the moderate climate change scenario A1B in an ensemble of all the published European model projections (adapted from Colette et al. 2015a).*

The main effect of climate responsible for this increase in surface ozone pollution in Europe is the increase in temperature and solar radiation leading to an increase in biogenic isoprene emissions even if a possible inhibition of these emissions with increasing $CO_2$ concentrations occurs in the long run, thereby yielding major uncertainties (Lathière et al. 2010; Langner et al. 2012). The other impacts of climate on surface ozone are the direct impact of an increase in temperature on the kinetics of atmospheric chemistry, and the direct impact of solar radiation on photochemistry resulting from changes in cloud cover. Both increase photolysis rates, particularly that of nitrogen dioxide, which favors the formation of ozone. In both cases, the increase in temperature and solar radiation can result from gradual changes in the average climate, but they are exacerbated in the case of extreme heat wave events. In addition to meteorological factors, heat waves favor the accumulation of pollution in the absence of atmospheric dispersion.

In the context of the MISTRALS/ChArMEx project, the global model outputs from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP; Young et al. 2013) are being analyzed to assess future changes in surface ozone over the Euro-Mediterranean region (Jaidan et al. in prep.). Under the pessimistic Representative Concentration Pathway (RCP8.5) scenario, mean temperature will increase by about 5.4K by 2100 compared to 2000 accompanied by a small increase (about 2%) in surface ozone.

Over European land surfaces, the 95% confidence interval of summertime mean ozone change is estimated to be [0.44; 0.64] and [0.99; 1.50] ppbv for the 2041–2070 and 2071–2100 periods, respectively. This change may seem small, but it is of the same order of magnitude as the ozone trends reported over Europe in the past two decades despite the implementation of ambitious policies (Monks et al. 2015; Colette et al. 2016). This raises serious doubts about our ability to compensate for the climate change penalty by controlling the emissions of ozone precursors.

## Particulate matter

The largest detrimental sanitary impacts of air pollution are currently attributed to atmospheric aerosols from various sources (WHO, 2013). Also called particulate matter (PM), they can originate from anthropogenic or biogenic gaseous precursors (this is the case for example of sulfate, nitrate, ammonium, and secondary organic aerosols), from primary emissions of particulate matter (e.g. elemental carbon (EC), but also heavy metals and persistent organic pollutants (POPs) such as polycyclic aromatic hydrocarbons (PAHs)), or from natural sources (desert dust, sea salt, volcanic ash).

Future changes in PM pollution in the context of adaptation to climate change is less clear than that of ozone because of the complexity of the often competitive processes involved (Fuzzi et al. 2015). Recent evidence points to a climate change benefit (with a reduction in PM loads, in particular because of an increase in volatility with increasing temperature; Lecœur and Seigneur, 2013; Colette et al. 2013; Lacressonnière et al. 2016; Lemaire et al. 2016) but increases have been reported in the southern parts of Europe (Manders et al. 2012; Hedegaard et al. 2013). Changes in biogenic precursor emission of secondary aerosols (SOA), which are likely to increase substantially in a warmer climate, could lead to an increase in PM concentrations (Megaritis et al. 2013). Changes in scavenging by precipitation, transport patterns and persistence of anticyclonic conditions leading to PM accumulation could also play a role in shaping future aerosol concentrations (Pausata et al. 2013). The frequency of precipitation is more likely to affect PM scavenging than the intensity of precipitation. Simulating accurate precipitation frequencies is very challenging for climate models, and projections are still subject to large uncertainties. Extreme heat events associated with stagnation of air masses are projected to increase, but the relative contribution of changes in their frequency and duration versus changes in the intensity of heat waves is not yet clear (Clark and Brown, 2013). PM pollution is likely to be more sensitive to the extended duration of the events.

The potential change in PM loads in southern Europe will be largely determined by the mineral dust fraction. Both advection from the Sahara and North African deserts and local mobilization e.g. from agricultural land during dry conditions (Bessagnet et al. 2008) contribute to this fraction. Global and regional climate changes as well as changes in land use may have significant impacts on dust emission and transport. African dust activity has been shown to be correlated with different aspects of climate variability including the El Niño/Southern Oscillation, the North Atlantic Oscillation, the meridional position of the intertropical convergence zone, Sahelian rainfall and surface temperatures over the Sahara Desert, which can affect surface wind activity to varying degrees (Evan et al. 2016). The same authors conclude that the likely tendency for African dust activity is a decrease in a warmer climate. However, changes in $PM_{10}$ exceedances due to dust over Europe are more likely to be sensitive to changes in the frequency and transport pathways of dust storms rather than to variations in mean emissions or in mean concentrations. Currently, there is no consensus on the sign and magnitude of future regional change in dust concentrations affecting Mediterranean regions and southern Europe.

As another source of natural aerosol, sea sprays, can account for a major fraction of PM in the coastal regions of Europe. Beside sea salts, a significant proportion of the submicron fraction of sea sprays is organic and comes from biogenic sources. Studies have revealed no significant trend in the activity of sea sprays in the North Atlantic in recent decades (Korhonen et al. 2011) and this is unlikely to change significantly with climate change (Jacobson and Streets, 2009).

Wildfires are another major source of aerosol and ozone precursors that can severely impact air quality (Hodzic et al., 2007; Miranda et al., 2008) and for which climate and land use change may be determining factors. A dryer climate would tend to increase wildfires but man-driven changes in land use also have a very strong impact, especially in Europe, where the population density is high. Landscape management and fragmentation and fire suppression tend to reduce wildfires (Knorr et al. 2014). For these reasons, an increase in fire frequency with climate change will not necessarily lead to a net increase in PM emissions as these are not only determined by the number of fires but also by their duration, extent and intensity.



# Mitigation: towards win-win solutions to limit global warming and improve air quality

The evolution towards a low carbon economy will be accompanied by reductions in the emission of air pollutants. A vast array of mitigation measures will have beneficial impacts on both air pollution and climate mitigation, of which several belong to the category of energy efficiency measures, which represent a very substantial pathway towards win-win solutions (Colette et al. 2015b), even if some strategies that favor climate mitigation may be detrimental to air quality (for instance the use of diesel fuel and the domestic burning of wood with outdated appliances).

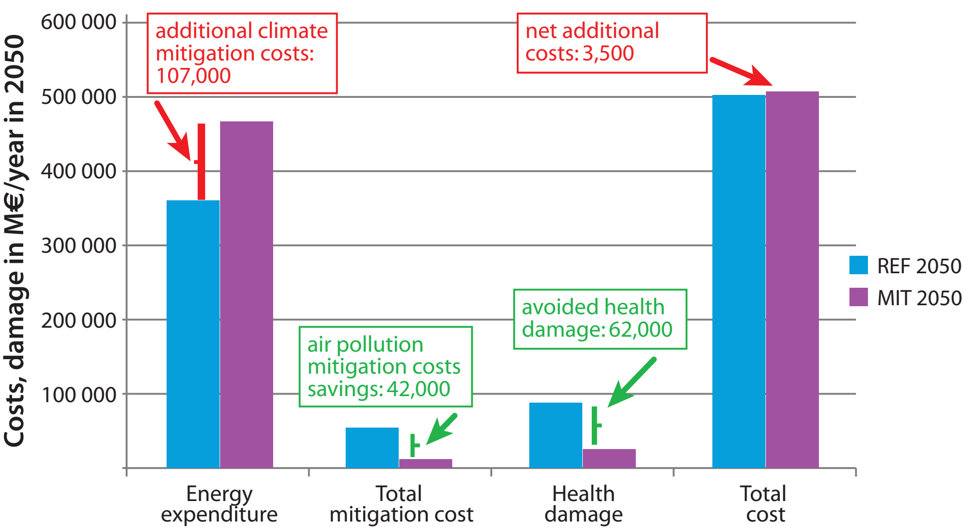


*Figure 12*
*Win-win strategies: cost benefit analyses at European scale demonstrate that the additional costs related to the climate mitigation (MIT) scenario aiming at limiting warming to 2 °C at the end of the 21st century compared to the business-as-usual scenario (REF) could be largely offset by savings in end of pipe air pollution mitigation costs and avoided damage to health. Adapted from* Schucht et al. *(2015).*

The sanitary benefits that can be expected from the future evolution of climate and air quality policies were quantified in IIASA (2013) and Likhvar et al. (2015), for example. These authors demonstrate that European countries located along the Mediterranean coasts will benefit the most from a reduction in ozone exposure.

A quantitative assessment of the costs and benefits associated with climate mitigation in Europe was proposed by Schucht et al. (2015). These authors found that the very substantial costs of shifting to an energy mix that would comply with the 2 °C warming target would be offset by the positive externality represented by reduced air pollution. This is because the low-carbon scenario also yields (i) reduced cost of end of pipe technologies and (ii) direct sanitary benefits (Fig. 12).



# Way forward

Recent evidence demonstrated the link between climate change and air pollution both regarding adaptation and mitigation strategies. It should be emphasized that, at present, most work has been performed at continental scale, through Europe-wide assessments, in addition to a few global studies (Anenberg et al. 2010; West et al. 2013; Lelieveld et al. 2015). There have been few dedicated assessments of such impacts on the Mediterranean region, thereby opening new research perspectives, in which the proposed contribution of the MISTRALS/ChArMEx Program could be instrumental.

Overall, major uncertainties remain on the likely evolution of aerosols, especially over southern Europe and the Mediterranean basin. Beside process studies, ensembles of high resolution modeling approaches combining climate and aerosols, and including land use change/management scenarios are one possible way to characterize key mechanisms and to quantify and reduce these uncertainties.

As far as climate adaptation is concerned, the role of climate change in land use and, in turn, in dust resuspension and dispersion remain a key uncertainty. The role of biogenic emissions, as ozone precursors, but also of secondary organic aerosols, is also an important topic.

There are win-win strategies to be developed in the years to come to improve air quality and to engage in progress towards a low carbon economy. Such benefits have been pointed out in several European studies, but the specific situation of Mediterranean countries deserves a closer look to tailor the most efficient sustainable strategies.

# Conclusion and recommendations



Ambient air is an important common resource. Its quality affects human and ecosystems health, and its composition impacts the regional climate. Climatological surveys show that atmospheric pollution in the form of both gaseous and particulate compounds is generally higher over the Mediterranean basin than over most European continental regions, especially during the long dry season, due to (i) the confluence of long range transported continental air masses that add to local sources of air pollution (e.g. heavy ship traffic), (ii) the scarce precipitation scavenging, (iii) intense photochemistry, and (iv) local circulations and poor ventilation rates that recycle polluted air layers in the western basin, or accumulate pollution in the eastern basin. Future levels of atmospheric trace compounds will be significantly impacted by the changes in climate conditions expected in the Mediterranean region, especially the significant increase in temperature and decrease in precipitation frequency. This will have, in turn, impacts on the Mediterranean climate and human health.

Atmospheric composition and air quality depend on natural and anthropogenic mechanisms, some of which are directly affected by climate change. This is the case of emissions of volatile organic compounds (VOCs) by vegetation, which depend on the temperature, photosynthetically active radiation and availability of water. The most recent observations made in the framework of ChArMEx show that climate change will likely lead to an increase in these emissions, which play a crucial role in the chemical formation of ozone and fine organic particles. But the impact of climate change on emissions is not always straightforward. This is the case of forest fire emissions that also play a role in ozone and particulate pollution. One could expect that a dryer climate would increase fire frequency and consequently particulate air pollution. Nevertheless, emissions by fires depend not only on their frequency, but also on their duration, intensity and extent. There is also no consensus on the impact of climate change on dust emissions. Although climate change will affect dust emissions, which depend on precipitation, land cover and surface wind, it is still uncertain whether these emissions will increase or decrease in the future, especially because dust emissions also depend on agriculture pressure and field preparation techniques. Neither is the effect of climate change on marine emissions of sea salt and VOCs (as marine VOCs depend both on the biological activity and environmental parameters) yet clear. Rather than the usually suspected sulfur compounds, iodine-containing compounds, whose emission is linked to seawater microorganisms, appear to be at the origin of new particle formation over the northwestern Mediterranean. Despite the fact anthropogenic emissions are also important contributors to the composition of the air, their quantification are still associated with considerable uncertainty. Finally, recent studies in large urban centers in the eastern Mediterranean basin indicate that large scale anthropogenic emission inventories are seriously underestimated. What is more, all these inventories agree on a marked increase in anthropogenic emissions of major pollutants in the Middle East area (MEA). Higher levels of primary emitted pollutants combined with higher temperature in the future will lead to more frequent intense pollution events that will have major health impacts in urban areas.

The level of pollution of Mediterranean air also depends on long range and intercontinental transport. Recent ChArMEx field campaigns identified air masses from North America and tropical Africa in the western Mediterranean and from South East Asia in the eastern Mediterranean. It was shown that imported Asian pollution builds up in the eastern Mediterranean, leading to a sharp west-to-east increasing gradient in aerosols and trace gases such as ozone and methane. These intercontinental pathways come into play under specific meteorological configurations that will be impacted by climate change. However, it is not yet known if climate change will favor intercontinental transport, or not.

The Mediterranean surface water ecosystem largely depends on atmospheric inputs for most of its crucial nutrients (N and P), especially in summer when thermal stratification prevents the upwelling of nutrients from deeper waters. Anthropogenic nitrogen and airborne dust deposition to nutrient depleted surface seawater could favor phytoplankton development and this fertilization effect may stimulate the transfer of atmospheric $CO_2$ to sediments, reducing atmospheric $CO_2$ and climate change. Due to air quality mitigation measures, it is also predicted than anthropogenic N fluxes will decrease in the coming years, limiting the atmospheric input of nutrients and possibly related biological activity. In addition, long term series of deposition measurements suggest that the atmospheric input of dust has decreased by one order of magnitude in the last decade compared to previous decades. The reasons are not well understood, satellite observations show that Saharan dust transport events are still common. Recent *in situ* studies in the northwestern Mediterranean showed that Saharan dust deposition by rain stimulates heterotrophic bacteria growth, which reemits $CO_2$. Thus, dust deposition has two opposite effects on the atmospheric $CO_2$ that need to be further studied in order to estimate the net effect at large scales.

One very important impact of atmospheric chemistry on the regional climate is the impact of aerosols on the water cycle, which is often neglected in climate models. The Mediterranean region is a special place where most of the moisture that fuels precipitation comes from evaporation from the Mediterranean basin. One direct effect of aerosols is reducing the solar energy delivered to the surface by scattering it back to space or absorbing it within turbid layers containing desert dust or carbonaceous aerosols. This dimming effect decreases surface temperature and consequently evaporation from the sea surface. Atmospheric models with externally forced sea surface temperature do not properly account for this effect, which can be simulated by atmosphere-ocean coupled models. A recent study performed in the framework of ChArMEx and HyMEX calculated that this radiative effect reduces the regional precipitation by 10%, which is a major issue in a region where water is already scarce. But aerosols can further reduce precipitation by indirect effects through aerosol-cloud interactions. Since water vapor condenses around aerosol particles to form the cloud droplets, an excess of aerosols leads to smaller cloud droplets that do not get big enough to fall. Another important and even more complex issue is the formation of ice crystals that trigger the precipitation cycle, which critically depends on the icing properties of aerosol particles. These properties are highly contrasted in different types of particles, some bacteria and soil dust being the most efficient. Aerosol-cloud interactions remain a major source of uncertainty in climate models and climate change projections, and should thus be an important field of study in the near future in the Mediterranean due to its possible impact on the scarcity of water resources.

The most dramatic effect of bad air quality is on human health. People poison themselves by breathing polluted ambient air, the result being chronic diseases or even premature death. Most inhabitants of the Mediterranean region, especially on the southern and eastern sides of the basin, are more or less regularly exposed to high loads (well above WHO air quality recommendations) in the form of soil dust particles, smoke emitted by forest fires, ozone, and anthropogenic emissions from almost unregulated large urban centers. All around the basin, the rare available epidemiological studies all show an excess of premature deaths associated with an increase in particulate pollution. Reducing pollution levels would reduce the death toll and hospital admissions, and prevention policies should be established with a view to reducing effects on health.

Recent evidence demonstrated the link between climate change and air pollution both regarding adaptation and mitigation strategies. There are important possible win-win strategies to be developed in the years to come to improve air quality while engaging in a process aimed at a low carbon economy. Such benefits have been pointed out in several European studies, but the specific situation of Mediterranean countries deserves more specific investigations.

To conclude, it is clear that both-way interactions between atmospheric chemistry and climate are not yet fully understood and quantified in the Mediterranean region. Robust predictions of the future living conditions in the Mediterranean require that such interactions are included in regional models. Positive feedback is expected between climate change and air pollution, but quantification of natural and anthropogenic emissions, process studies, and the development of chemistry-transport models are still necessary for a good assessment of future regional atmospheric environmental and climate conditions. In particular, *air pollution health* risk *assessment* is still lacking at the regional scale and requires a major research effort on the southern and eastern side of the basin where the dose-response functions established in well-developed countries can be questioned.

## Acknowledgements

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**Part 2**

# Vulnerability and impacts

< © IRD/R. Simenel – The semi-arid North African environment is particularly subject to climate change. Souss, Morocco, 2012.

# Climate change impacts on marine ecosystems and resources

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## Abstract

The Mediterranean Sea is one of the biggest reservoirs of biodiversity in the world. Millions of people directly or indirectly depend on the ecosystem services it provides, in particular the provisioning of fisheries resources. Rather than a hot-spot of biodiversity, the Mediterranean Sea has now become a hot-spot of global change where climate change and other anthropogenic pressures (e.g., overfishing, pollution, habitat destruction) operate independently or synergistically to shape an altered Mediterranean Sea that may shift from the today picture. The set of physical-chemical changes triggered by climate change may disrupt the functioning of the biological components of ecosystems, from the individual up to the ecosystem scale, from the basis of the food webs (macrophytes, phytoplankton) up to the higher trophic levels (e.g., predator fish). Current research shows that the physiology and fish life history traits have changed, that fish distribution areas are moving northward and eastward, thus modifying the structure and the species composition of the communities. The dynamics of populations and food webs are modified as well, and species invasions increase at an unprecedented rate. Combined with fishing, climate change renders marine ecosystems more vulnerable to anthropogenic pressures, to natural hazards and to invasions by non-indigenous species. Although uncertainties remain with regard to the magnitude of expected ecological changes, the projections based on IPCC scenarios all confirm that climate change is a serious threat for the biodiversity and the sustainable exploitation of fishing resources in the Mediterranean Sea. This calls for the reinforcement of innovative and integrated research and assessment capacities to support an ecosystem-based management at the scale of the Mediterranean basin.



## Résumé

La Méditerranée constitue l'un des plus grands réservoirs de biodiversité à l'échelle mondiale. Des millions de personnes dépendent directement ou indirectement des services écosystémiques rendus par celle-ci, notamment l'approvisionnement en ressources marines. Plus qu'un point chaud de biodiversité marine, la Méditerranée est désormais un point chaud du changement global où changement climatique et autres pressions d'origine anthropique (e.g. surexploitation, pollution, destruction d'habitat) peuvent agir indépendamment ou en synergie pour former une Méditerranée différente de celle que nous connaissons aujourd'hui. L'ensemble des modifications physico-chimiques induites par le changement climatique conduit à un bouleversement des composantes biologiques des écosystèmes, de l'échelle individuelle à l'échelle écosystémique, des producteurs primaires (algues, phytoplancton) aux plus hauts niveaux trophiques (e.g. poissons prédateurs). Les recherches actuelles démontrent que la physiologie et les traits de vie des poissons changent et que leurs distributions spatiales se sont décalées vers le nord et l'est, modifiant la structure et la composition des communautés. La dynamique des populations et des réseaux trophiques s'en trouve également modifiée et les invasions biologiques se multiplient à un rythme encore jamais observé. Avec la pêche, le changement climatique induit une fragilisation des écosystèmes marins, rendant ces derniers moins résilients et plus instables face aux activités anthropiques, aux aléas naturels et aux invasions d'espèces exotiques. Bien que des incertitudes demeurent quant à l'ampleur des changements biologiques en Méditerranée, les projections faites à partir des scénarios émis par le GIEC s'accordent pour affirmer que le changement climatique est une sérieuse menace pour la biodiversité marine et la production de ressources vivantes. Il s'agit alors d'appuyer des systèmes de recherche et d'évaluation innovants et intégrés afin d'adopter une gestion écosystémique à l'échelle du bassin méditerranéen.

# Introduction

The Mediterranean Sea is a hotspot of biodiversity. It hosts 4% to 18% of all identified marine species, which is considerable given that the Mediterranean Sea only accounts for 0.82% of the global ocean surface (Coll et al. 2010). Considered as a "factory" designed to produce endemics, the unique geological history of the Mediterranean Sea and the variety of climatic and hydrological situations have led to the co-occurrence of cold, temperate and subtropical biota (Lejeusne et al. 2010). This biodiversity hot-spot is at risk today as a result of multiple pressures. Based on global climate change projection scenarios, the Mediterranean Sea has been classified as one of the most responsive regions to climate (Giorgi, 2006). The Mediterranean Sea is also known to be the biggest recipient of exotic species with the rate of species introduction peaking at two species per ten-day period in the 2000s (Ben Rais Lasram and Mouillot 2009, Zenetos et al. 2010). Combined with critical overfishing (more than 90% of assessed-stocks were overfished in 2015 (STECF 2016)), pollution and habitat destruction, climate change may result in the Mediterranean Sea becoming a hot-spot of global change (Micheli et al. 2013).

In this chapter, we describe how marine ecosystems and resources have shaped and, through interlinked mechanisms, may continue to shape future responses to climate change: (i) changes in primary production and in the structure of foodwebs, (ii) changes in population dynamics and life history traits, (iii) changes in species distribution range and habitats, and (iv) changes in the invasion rate of non-indigenous species. Examples are provided from different regions of the Mediterranean Sea and different biota (with a focus on fish communities), whereas marine top predators such as birds and marine mammals are not included in this review. Interactions between climate change, overfishing and habitat destruction are discussed throughout the chapter, but interactions with other direct anthropogenic pressures such as pollution, shipping, and oil spills are not addressed here.

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# Climate change impact on planktonic production in the Mediterranean Sea

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## Primary production and plankton communities in the Mediterranean Sea

The Mediterranean Sea is characterized by a gradient of growing oligotrophy from the northwestern regions to the Levantine basin (Bosc et al. 2004). Nutrient availability is generally low, resulting in low phytoplankton biomass (less than 0.25 mg/mL). However, blooms and peaks in zooplankton biomass are recorded in areas of complex physical dynamics (winter convection, fronts, and gyres, Siokou-Frangou et al. 2010).

Seasonal hydrological regimes structure the phytoplankton community (Marty et al. 2002; Marty and Chiavérini 2010). Seasonal patterns are linked to variations in hydrological features and changes in nutrient concentrations: peaks in biomass occur in spring (March-April), after the replenishment of nutrients in surface waters owing to winter water mixing. After spring, the phytoplankton biomass decreases and goes deeper in the water column. Relying on satellite observations, D'Ortenzio and Ribera d'Alcalà (2009) defined a bioregionalization of the whole basin. Their classification provided a clear picture of the different phytoplankton trophic regimes in the Mediterranean. Nearly 60% of the basin's surface was described as « non-blooming » (mainly the eastern regions and the southwestern basin). Conversely, the northernmost regions, the Alboran, and the region of Rhodes were shown to be zones of « intermittent blooming » (gradual growth of biomass between September and February, linked to the deepening of the mixed layer). The locations of the different trophic regimes are clearly linked to convection and deep water formation processes (Millot and Taupier-Letage 2005). Primarily wind driven physical forcings favor the development of the phytoplankton by re-injecting nutrients (nitrates and phosphates) into the surface waters through mixing of the water column (Sverdrup 1953). This has a strong impact on the structure of the phytoplankton community.

Depending on the trophic regime, different phytoplankton taxa are likely to constitute the communities. Marty et al. (2002) analyzed algal pigment content to explore the relative contribution of different taxa to total phytoplankton biomass. These authors found that spring blooms were dominated by diatoms (large micro-algae characterized by silica shells), while stratifying conditions favor the development of nanoflagellates (nanophytoplankton), which are then replaced by cyanobacteria (picophytoplankton). The two latter phytoplankton size classes can be considered as markers of oligotrophic conditions, while microphytoplankton (diatoms) are opportunistic and burst after nutrient replenishment. Over the year, nanophytoplankton account for 43% to 50% of the total primary production of the Mediterranean Sea, which is largely dominated by Prymnesiophyta (Uitz et al. 2012). Even the blooming areas investigated by D'Ortenzio and Ribera d'Alcalà (2009) were dominated by nanophytoplankton, except in spring when they were replaced by microphytoplankton (up to 38% of total primary production). In non-blooming zones, picophytoplankton come after nanophytoplankton in order of abundance.

To date, offshore surveys of plankton distribution and communities have been dispersed not only in space and time, but have also used different methods (Siokou-Frangou et al. 2010). Consequently, regional and seasonal patterns of diversity and community composition are still poorly understood.

Concerning phytoplankton diversity, low biomass is linked to the dominance of the smallest plankton, which consist of picophytoplankton (mainly prochlorophytes), cyanobacteria (Synechococcus) and flagellates (Marty et al. 2002; Uitz et al. 2012). Non-colonial picodiatoms have occasionally been reported to be abundant, but cell size usually prevents their accurate identification. Nanophytoplankton, which are mainly composed of small flagellates, dinoflagellates, coccolithophores, and to a lesser extent of some small solitary diatoms, are also very abundant. Major increases in biomass are correlated with the growth of microphytoplankton, which are mainly composed of large colonies of diatoms (Marty et al. 2002; Marty and Chiavérini 2010). The main genera are *Asterionellopsis*, *Chaetoceros*, *Pseudo-nitzschia*, *Thalassionema* and *Thalassiosira* (Siokou-Frangou et al. 2010). These genera are unevenly distributed in the Mediterranean basin:

healthy colonies of *Chaetoceros* and *Pseudo-nitzschia* have been observed in areas of deep convection while colonies of *Chaetoceros*, in association with *Thalassiosira*, *Proboscia*, *Rhizosolenia* and *Leptocylindrus* have been found across fronts and gyres (circular oceanic surface currents). Although among the less abundant microplankton, dinoflagellates show significant diversity in the Mediterranean; like nanoplankton, they are associated with stratified and nutrient-depleted conditions. These taxa exhibit wide trophic modes: some are heterotrophic, while others are mixotrophic (*Neoceratium spp*.) or host endosymbiotic cyanobacteria. To summarize, Mediterranean phytoplankton comprise very diverse taxa with diverse ecological preferences.

Regarding zooplankton, the world dominance of copepods in the water column also applies to the Mediterranean. Like micro-algae, smaller species (< 2 mm) prevail in the communities, whatever the trophic regime (Siokou-Frangou et al. 2010). The bulk of zooplankton comprises very diverse genera of calanoids and cyclopoids. The relative contribution of the smaller cyclopoids is thought to increase with the increasing west-east gradient of oligotrophy, while larger species are more abundant in colder and more productive areas (Siokou-Frangou et al. 1997).

Other zooplankton taxa should not be overlooked. Cladocerans are found in large numbers in summer in coastal environments (Riandey et al., 2005). Gelatinous filter-feeders, like salps, frequently produce spectacular blooms in warm waters. Outbursts of jellyfish in summer have become a public concern. Gelatinous-wise, chaetognaths and siphonophores are carnivorous species frequently encountered in the Mediterranean Sea that prey on copepods and other smaller planktonic organisms.

## Climate variability influences plankton distribution and community composition

Plankton abundance and distribution are strongly controlled by hydrological features and water mass advection. The tight coupling between their population dynamics and climate makes them optimal indicators to monitor the impact of climate variability on ecosystems (Hays et al. 2005). Tunin-Ley et al. (2009) assembled time series to investigate the effects of increasing temperatures on the distribution of 46 *Ceratium* species (Dinoflagellates) over the 20$^{th}$ century (1908-2005). Irrespective of the location, species composition showed a clear seasonal cycle, but phenologies differed according to the species and the sites surveyed. Although *Ceratium* assemblages did vary with changing temperatures, contrary to expectations, thermophilic species did not show increasing trends. As no new species were detected during the 20$^{th}$ century, the disappearance of species that prefer colder conditions could not be balanced, and warming has resulted in a loss of biodiversity.

Marty and Chiavérini (2010) monitored hydrological changes in the Ligurian basin and their biogeochemical consequences during the period 1995-2007. These authors revealed an increase in phytoplankton biomass (+1.5 mgChla/$m^2$.yr) paralleling increases in temperature and salinity in the northwestern Mediterranean Sea. Furthermore, the fraction of biomass attributed to diatoms also increased. Thus, the increases in biomass were due to generalized growth of phytoplankton, not only to the growth of the smaller size classes that usually dominate in warmer conditions. Marty and Chiavérini (2010) reported an increase in the frequency of mixing events, rather than longer stratification periods.

Long time series provide ideal material to study plankton dynamics under climate change. Several multidecadal surveys have been conducted in the Mediterranean Sea (Berline et al. 2012), all of which evidenced strong seasonal patterns in phytoplankton and zooplankton communities (Ribera d'Alcalà et al. 2004). In the Gulf of Naples for instance, a time series from 1984 to 2000 revealed an over decadal decrease in phytoplankton (Ribera d'Alcalà et al. 2004), together with an increase in a rare copepod species and a weak decrease in zooplankton biomass. These authors suggested that biological rhythms regulate the temporal dynamics while the climate modulates the amplitude of the growth periods. This hypothesis was later invalidated by Mazzocchi et al. (2011) using the same time series, by providing evidence for phenological changes in Mediterranean mesozooplankton: the copepod assemblage characterizing spring and summer conditions declined over the study period as its typical high production season became shorter and started earlier in the year. By contrast, the communities that depend on summer and fall conditions remained stable phenology-wise, and were quite resilient to decreases in phytoplankton biomass. From these results, Mazzocchi et al. (2011) concluded that the zooplankton composition does not vary according to phytoplankton variability, and that zooplankton communities are resilient to climate change. This conclusion was challenged by Conversi et al. (2009), who demonstrated a dramatic shift across the copepod community between the late 1980s and the early 1990s. Warming combined with changes in circulation in the Ionian Sea (Civitarese et al. 2010) have been identified as the principal causes. The link between climatic variability and phytoplankton dynamics is consequently not well understood yet.

To summarize, plankton assemblages in the Mediterranean have proved to be good indicators of environmental changes. The variety of trophic regimes and the diversity of biological communities offer great opportunities to test hypotheses concerning climate change and its impacts on plankton. The Mediterranean Sea contains a wide range of plankton whose environmental preferences and functional roles remain to be fully determined. The patterns described above suggest differences between the ecological traits and environmental preferences of species. By altering the pelagic environment, anthropogenic climate change could alter plankton distribution, as well as their importance in the food web.



## How will anthropogenic climate change impact Mediterranean plankton?

Despite the importance of plankton for both food webs and biogeochemical cycles, very few studies have attempted to forecast the impact of climate change on primary production and community composition in the Mediterranean Sea (Lazzari et al. 2013; Herrmann et al. 2014). There are projections at the global scale, but the corresponding models do not adequately resolve the peculiar regional processes of the Mediterranean, and regional coupled models thus need to be implemented.

Focusing on the northwestern areas of the basin (Gulf of Lion and Ligurian Sea), Herrmann et al. (2014) investigated the response of the pelagic plankton ecosystem and associated carbon cycle, to long term changes in oceanic and atmospheric circulation. Their predictions suggest that climate change will not modify the seasonal dynamics and variability of the planktonic ecosystem at a first order, compared to what is modeled for the contemporary period. Microphytoplankton and nanophytoplankton biomasses are not expected to increase by the end of the 21st century. Meanwhile, their model forecasts an increase in zooplankton biomass, due to a gain in the smaller size fractions (nanozooplankton), and in picophytoplankton biomass. Their study suggests that climate change in the northwestern Mediterranean will favour the smallest components of the plankton, and strengthen the microbial loop activity.

Lazzari et al. (2013) used a different model that covered the entire Mediterranean Sea to assess the impact of climate change on the carbon cycle in a plankton ecosystem model. Like Herrmann et al. (2014), their model predicts a strengthening of the microbial pathway in the plankton ecosystem with reduced nutrient availability and phytoplankton biomass.

In contrast to higher trophic levels (Ben Rais Lasram 2010; Albouy et al. 2012), the potential impact of rising temperatures and salinity on plankton species composition has never been assessed. This will be crucial to better understand how climate change could reshape plankton in the Mediterranean Sea, as not all species share similar traits and functions in the ecosystems (Benedetti et al. 2016). In the future, more modeling studies are needed to better constrain the predicted impacts of climate change on primary production and plankton size structure. Models should also focus on resolving taxonomic and ecological complexity by accounting for differences in plankton species traits. Finally, multi-trophic models should be developed to estimate how climate change may impact the structure of the food web and ecosystem services provision.



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# Climate change induces bottom-up changes in the food webs of the Mediterranean Sea

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At the global scale, one of the main effects of climate change on marine ecosystems is changing the rate and patterns of primary production (Brown et al. 2010). In the Mediterranean Sea, although there is no consensus and no clear trends have emerged, several studies expect that, by increasing the vertical stability of the water column and by decreasing nutrient replenishment, seawater warming will cause changes in phytoplankton bloom phenology, biomass and community structure (Goffart et al. 2002, Bosc et al. 2004, Tunin-Ley et al. 2009). What has been clearly demonstrated is that seawater warming will lead to a shift in dominant species towards smaller species (picophytoplankton and nanoflagellates) and a decrease in diatoms (The MerMex Group 2011). Moreover, acidification in the Mediterranean Sea will strengthen the expected impacts, with an expected decrease in the biomass of calcifying organisms such as coccolithophorids, which are important plankton primary producers (Dias et al. 2010, The MerMex Group 2011). Primary and secondary production (i.e. the production of phytoplankton and zooplankton, respectively) play a key role in biogeochemical cycles, as well as in the structure and functioning of food webs and in global productivity of marine ecosystems. Through bottom-up or wasp-waist trophic controls (Cury et al. 2003), changes at the base of the food webs may transfer from low to high trophic levels, with potential impacts on the production of living resources and fisheries. Moreover, since the Mediterranean is a semi-enclosed sea, expected impacts of climate change on phytoplankton communities and their dynamics could affect ecosystems much more rapidly than in other oceanic regions (Lejeusne et al. 2010, Siokou-Frangou et al. 2010). In this chapter, we describe how climate change could affect the functioning of marine systems, and more specifically, the production of living resources by bottom-up control. We use a few typical recent examples to show how the strength of the bottom-up control and the base of the food web in the Mediterranean Sea could be affected by several hydrological changes and how these changes could affect food web dynamics, catch potential, and conservation of the marine biodiversity in the future.



## Changes in primary and secondary production affect food web dynamics and recruitment

At the global scale, under the IPCC SRES (Intergovernmental Panel on Climate Change Special Report on Emission Scenarios) A2 scenario, and based on the output of four global coupled carbon cycle-climate models, Steinacher et al. (2010) suggest that global mean primary production may decrease by 2% to 20% by 2100 relative to preindustrial conditions. In the Mediterranean Sea, by increasing the strength of the vertical stratification, warming could affect the turbulent nutrient supply to the photic layer and hence could reduce primary production (Marbà et al. 2015), as well as reduce the relative contribution of larger cells (The MerMex Group 2011). There are still many uncertainties on the level of impact of sea warming and of acidification on primary production in the basin, but it is clear that physical-chemical changes will affect the magnitude, timing and composition of phytoplankton blooms, with associated changes in the seasonal distribution of zooplankton (see sub-chapter 2.1.1 for more details).

It is now recognized that primary production is critical to maintain biodiversity and support fishery catches in the world's oceans (Brown et al. 2010). Indeed, more than 90% of ocean productivity is ensured by phytoplankton, which is then transferred throughout the food webs by grazing and predation and lost through metabolism (Lindeman 1942, Gascuel et al. 2008). Few studies have tried to forecast potential changes in primary and secondary production and the ensuing impacts on food webs and on the functioning of Mediterranean ecosystems. Many uncertainties remain concerning the magnitude of the expected climate-induced changes. Nevertheless, based on studies of other ecosystems in the world, it is possible to extrapolate the consequences of changes in primary production in this region. For instance, Chassot et al. (2010) showed that phytoplankton primary production influences global fisheries production at the scale of Large Marine Ecosystems (LME). This assumption was confirmed by Blanchard et al. (2012), who showed that, in 11 large regional shelf seas, potential marine fisheries production is primarily determined by available primary production. Similarly, using an ecosystem model, Brown et al. (2010) demonstrated that changes in primary production affect fisheries catch and value and have major implications for the conservation of marine biodiversity. Finally, at local, regional and global scales, several authors have established that fluctuations in fishery yields are linked to fluctuations in phytoplankton, zooplankton and benthic communities (e.g. Darnaude et al. 2004, Edwards & Richardson 2004, Cheung et al. 2010, Barange et al. 2014).

In the Mediterranean Sea, previous observations already suggested that a reduction in primary production linked to an increase of sea surface temperature could have negative impacts on fisheries catch and could exacerbate current trends of overfishing. This hypothesis was confirmed by Cheung et al. (2011) whose models predict that if phytoplankton communities shift towards smaller size cells, energy transfer from primary production to higher trophic levels may decline in the future, with an associated reduction in catch potential (see sub-chapter 2.1.4). Moreover, a decrease in primary production could be detrimental for the conservation of taxa of interest and for overall biodiversity in a context of global change, with potential synergies with overfishing, habitat degradation and biological invasions.

In marine ecosystems, environmental conditions play an important role in fish recruitment (i.e. the number of fish that survive from the early larval stage to reach the recruitment stage that can be targeted by fisheries). As fish larvae are very vulnerable to starvation, their survival strongly depends on prey availability, meaning the mean size of prey, their seasonal timing and abundance (Beaugrand et al. 2003) are crucial. The match-mismatch hypothesis (Cushing 1990) emphasizes that the production of first feeding larvae must match the production of planktonic food. Thus, by affecting primary and secondary production and timing, climate change may disrupt the distribution and phenology of fish larvae, affect recruitment and production of fish stocks, with indirect effects on food web structures and ecosystem-level changes (Edwards & Richardson 2004, Brander 2010). In the Mediterranean Sea, projected changes in primary and secondary productions suggest that trophic mismatches between fish pre-recruits and their prey could increase in the future, with negative consequences for recruitment success, sustainable fisheries and conservation of biodiversity (Lejeusne et al. 2010, Stergiou et al. 2015).

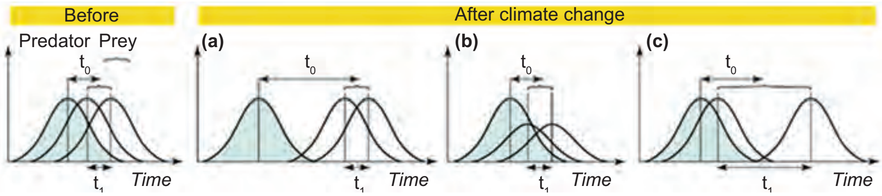


*Figure 1*
*Match-mismatch hypothesis and three possible effects of climate change:*
*(a) Change in the timing of prey peak production; (b) Change in the level of prey abundance;*
*(c) Change in the amplitude of year-to-year variations in prey timing in regions where inter-annual variability in temperature is expected to increase. $t_0$ is the degree of time mismatch, $t_1$ is the inter-annual variability in the timing of prey population.*
*From Cury et al. (2008).*

In addition to impacts on plankton production and timing, climate change can also lead to changes in the composition of species that form the base of marine food webs. In the Mediterranean Sea, the increase in water temperature has already modified jellyfish population dynamics (Coll et al. 2010). For several decades, the extent and intensity of jellyfish outbreaks have increased, in particular outbreaks of *Pelagia noctiluca*, a planktonic predator of fish larvae and of their zooplankton prey (Licandro et al. 2010). In the western Mediterranean, the increasing frequency of these outbreaks can be explained by the alteration of the trophic structure of ecosystems due to overfishing and/or eutrophication on the one hand, and by sea warming and changes in surface hydrography on the other (Licandro et al. 2010, Canepa et al. 2014). As already shown in the Black Sea, outbreaks can affect fisheries by bottom-up and top-down controls on fish larvae survival (Daskalov et al. 2007). In fact, jellyfish can affect fish recruitment negatively and as they can be venomous, outbreaks can also be detrimental to aquaculture and have strong ecological and socio-economic impacts. Considering the current IPCC projections, Licandro et al. (2010) suggested that outbreaks of *P.noctiluca*, along with other jellyfish species, may become more frequent in the Mediterranean basin and extend over a longer period of the year than previously, causing alteration of the pelagic food web and thereby reducing fishery production. For instance, in the northwestern Mediterranean Sea, Molinero et al. (2005) found that the increase in jellyfish outbreaks during the 1980s was largely favored by high positive temperature anomalies. They highlighted the trophic cascade that took place during the mid-late 1980s, with the high abundance of jellyfish and a marked drop in the abundance of copepods. However, the variability of copepods has direct implications for pelagic fish populations and for the biological pump of carbon into the deep ocean (Ohman & Hirche 2001, Calbet 2008). Thus, the Mediterranean pelagic ecosystem could shift towards an alternative state with less organic matter exported and prone to the risk of high trophic level predators (exploited by fisheries) being replaced by jellyfish (Gros 2011).

Another consequence of climate change in the Mediterranean Sea, which, at first sight, has less impact on fisheries, is the increase in the mucilage phenomenon. Indeed, surface water warming and the associated increase in water column stability can favor the coalescence of marine snow (i.e. small amorphous aggregates with colloidal properties) into marine mucilage (Danovaro et al. 2009). Danovaro et al. (2009) have shown that the majority of mucilage spreading is linked to climate-driven sea surface warming. The occurrence of mucilage events is increasing and spreading to several regions beyond the Adriatic Sea. Mucilage can act as a controlling factor for microbial diversity and could act as a carrier of specific microorganisms, thereby increasing the spread of pathogenic bacteria (Danovaro et al. 2009). According to these authors, if the mucilage phenomenon continues to increase in frequency and duration and to extend its range in the region, the increased frequency and extension of some marine diseases may have consequences for human health; "a warmer world would be a sicker world" (Harvell et al. 2009). Mucilage, in turn, can induce hypoxic phenomena, extensive anoxia and may reduce the provision of ecosystem services and ecosystem resilience. Indeed, hypoxia or anoxia events can cause the suffocation of benthic and epibenthic organisms on the sea bottom, which, in turn, could result in severe fishery and sanitary problems (Danovaro et al. 2005). Moreover, because of mucilage's properties, the phenomena may clog fishing nets causing serious socio-economic damage for fisheries (Rinaldi et al. 1995).

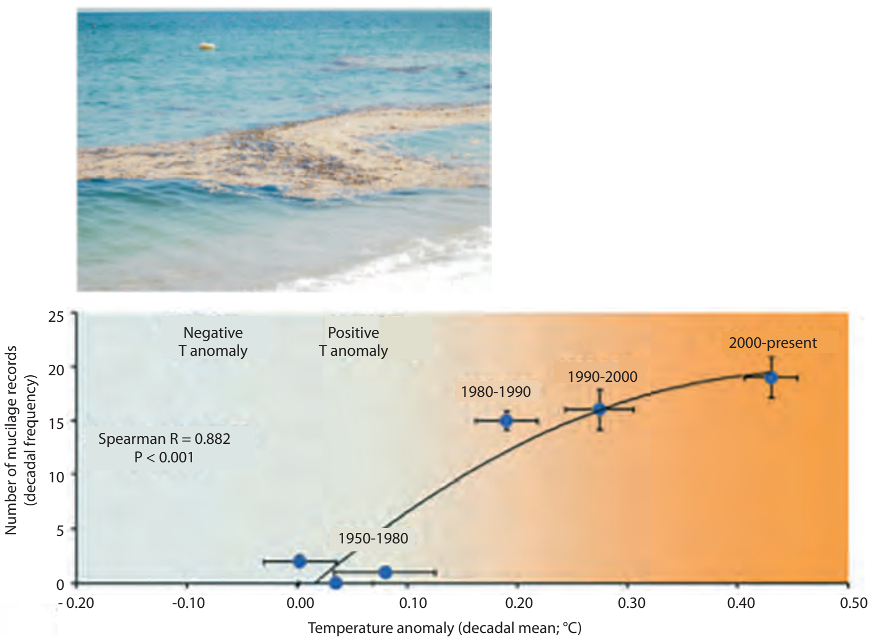


*Figure 2*

*Relationships between mucilage occurrence in the Mediterranean Sea and climate change (as magnitude of the thermal anomalies) on a decadal basis. Photo of mucilage in surface off-shore waters. Adapted from Danovaro et al. (2009).*

# Climate change drives commercial fish production

Because of their short life span, their nutrition relying on short plankton-based food chains and their recruitment controlled by the environment, pelagic fish stocks are excellent sentinel species for analysis of the effects of climate change on ecosystems (Checkley et al. 2009). This is not surprising, given that these species have a very high growth and population turnover rate, making them more susceptible to changes in the environment. For example, in the western Mediterranean, a significant relationship was found between round sardinella (*Sardinella aurita*) landings and temperature anomalies (Sabates et al. 2006). Indeed, a gradual northward increase in the abundance of this warm water species was observed along the Mediterranean Iberian coast. Consequently, an overall increase in landings of round sardinella has been observed over the last 30 years (around 35 000 t), while landings remained below 5000 t year$^{-1}$ until the early 1980s. This increase is linked to the successful reproduction of the species, marked by an increase in larval abundance, in the northwestern Mediterranean. At the same time and in the same area, landings of two other pelagic species, sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicolus*), have declined in recent decades. Sprat (*Sprattus sprattus*), a cold water small pelagic species, has virtually disappeared from commercial catches of the northwestern Mediterranean (Sabates et al. 2006). Using a 3-D full life cycle population model at the Mediterranean Sea LME (large marine ecosystem) scale, under the SRES IPCC A1B scenario, Stergiou et al. (2015) determined that the anchovy biomass would decrease significantly (by around -28 %) in 2080-2100 compared to 1980-2000. This prediction is linked to a decrease in zooplankton biomass and rising temperatures that affect fish metabolic rates (i.e. an increase in maintenance cost). In their study, sea warming was shown to affect net fish somatic growth and to indirectly affect egg production, which is weight dependent. Moreover, with warmer temperatures, fish early life stages could be subject to higher starvation mortalities due to the increased energy required to meet maintenance costs (Stergiou et al. 2015). As a result, anchovy stock biomass is predicted to decrease by 33% in the Adriatic sub-area, by 18% in the north Aegean sub-area and by 15% in the Catalan Sea/Gulf of Lions sub-area.

In the northwestern Mediterranean, numerous changes in environmental conditions such as riverine input or wind mixing can explain fluctuations in the productivity of small pelagic fish (Lloret et al. 2004). For instance, a significant relationship between monthly landings of anchovy and freshwater inputs of the Ebre River during the spawning season of anchovy has been found (Lloret et al. 2004). For sardine, monthly landings were positively correlated with wind mixing during its spawning season (Lloret et al. 2004). Thus, in a context in which climate change is expected to increase variance in rainfall regimes, with increased frequency of droughts paralleled by unusual amounts of rainfall and floods, increasing temperature and changing wind mixing, pelagic fish stocks in the Mediterranean are likely to be strongly impacted (Lloret et al. 2001). In the northwestern Mediterranean, in contrast to anchovy, sardine abundance was found to be negatively correlated with sea surface temperature, and the warming trend may have contributed both to the decrease in sardine abundance and to the extension of the distribution area of the round sardinella (Palomera et al. 2007, Rijnsdorp et al. 2010). In addition to climate change impacts, fluctuations in small pelagic populations have also been shown to be associated with interdecadal variability of climate indices, such as the well-known Atlantic Multidecadal Oscillation (AMO) and the more local Western Mediterranean Oscillation (WeMO) indices (Martín et al. 2012, Alheit et al. 2014).

Pelagic fish are essential trophic compartments of marine ecosystems due to their high biomass at intermediate levels of the food web, and therefore their key role in the transfer of organic matter from lower to higher trophic levels (Cury et al. 2000, Palomera et al. 2007). Hence, variability in small pelagic fish due to climate change or other anthropogenic disturbances will modify both the structure and functioning of ecosystems (Cury et al. 2000). Pelagic stocks are not the only stocks to be impacted by changes in river discharge. Salen-Picard et al. (2002) showed that the Rhone river flow in the Gulf of Lion also influenced abundances of *Solea solea* by causing pulses of organic matter that are followed by peaks of polychaetes density. Indeed, a positive correlation was found between the mean annual commercial landings of *S. solea*, with a time lag of five years, in two fishing harbors close to the Rhone delta (Salen-Picard et al. 2002). The authors of the study concluded that fluctuations in sole fishery yield in the Gulf of Lion can be influenced by climate, as the Rhone river flow is related to the North Atlantic Oscillation, which drives precipitation over Western Europe. In fact, a decrease in run-off into the Mediterranean Sea could reduce the productivity of sole and other demersal fish in this region (Salen-Picard et al. 2002, Darnaude et al. 2004). By coupling a hydrodynamic model to the food web model Ecopath with Ecosim, Libralato & Solidoro (2009) showed that changes in river run-off are the major environmental driver of ecosystem dynamics in coastal areas in the Adriatic, especially the Lagoon of Venice.

To summarize, many uncertainties remain on future change in primary production and more data are needed to carefully assess possible impacts on marine biodiversity and on fisheries production. With this synthesis, we highlight a possible change in the strength of the bottom-up control in the Mediterranean ecosystems. Small pelagics are influenced by a plethora of factors, each of which can be altered by climate change, so that they can have additive, synergistic or antagonistic effects on small pelagics. Climate change is expected to reduce primary production rates at basin scale, to alter the phenology of phytoplankton and zooplankton blooms and to cause shifts in community structures. All these changes will have dramatic impacts on the structure and functioning of ecosystems, and especially on food web dynamics. For fisheries, the change in primary production will likely result in a reduction of catches and/or an exacerbation of the effects of overfishing. Finally, by affecting rainfall regimes, and therefore river outflows, climate change could affect the overall food web and fishery production on the continental shelf.

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# Climate change impacts on marine resources

## From individual to ecosystem responses

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Temperature has a major direct effect on the physiology, growth, reproduction, recruitment and behavior of poikilothermic organisms such as fish. It affects many physiological processes ranging from damaging proteins to disrupting organ function. Environmental changes, especially climate warming, may thus strongly influence the abundance and biogeography of fish through species-specific physiological thresholds of temperature tolerance, or through responses to changes in other trophic levels (Perry et al. 2005, Sabates et al. 2006, Rijnsdorp et al. 2009). Organisms tend to adapt to local environmental temperatures, with optimal physiological responses matching temperatures that are close to the environmental average (Hoegh-Guldberg & Bruno 2010). In this context, shifts in the spatial distribution range of marine organisms are among the most perceptible consequences of climate change at the world scale, with potentially significant impacts on commercial fisheries (Perry et al. 2005), on food webs and ecosystem functioning (Doney et al. 2012, Albouy et al. 2014), and on biodiversity as a whole (Harley 2011, Bellard et al. 2012).

The warming of the Mediterranean Sea affects the fitness of marine biota as already shown by records of changes in abundance, survival and fertility, phenology and species migration (Marbà et al. 2015). Population abundance and survival are the biological variables are the most frequently reported impacts of Mediterranean warming, followed by migration of native and introduced species (Marbà et al. 2015). However, the sensitivity of Mediterranean biota to warming varies across taxonomic groups (Marbà et al. 2015), from primary producers to high trophic levels, with possible synergistic effects with other anthropogenic impacts such as high exploitation (Harley et al. 2006). In this chapter, we use examples to analyze the expected impacts of climate change on marine organisms in the Mediterranean Sea, with a focus on fish, and to investigate possible responses from individual to ecosystem level. It is important to bear in mind that in the Mediterranean Sea, the effects of climate change occur in parallel with other human-driven effects such as overfishing, pollution, and habitat degradation (Coll et al. 2010), and can have cumulative effects, frequently of synergistic nature (Calvo et al. 2011).

## Climate change affects functional traits of fishes

Several studies have shown that changes in temperature and in ocean chemistry affect the growth, reproduction and physiology of marine organisms (Pörtner & Knust 2007, Sumaila et al. 2011). It was recently shown that fish body size may be reduced due to climate change, especially in response to warming, reduction in oxygen, and resource availability (Daufresne et al. 2009, Sheridan & Bickford 2011, Cheung et al. 2013) (Figure 1). In a meta-analysis of the effect of climate on fish body size, Daufresne et al. (2009) showed a significant increase in the proportion of small-sized species and young age classes and a decrease in size-at-age, in accordance with Bergmann's rule concerning temperature vs. size. According to the IPCC (Intergovernmental Panel on Climate Change), oceans are projected to become warmer and less oxygenated (IPCC 2014). As a consequence, in the Mediterranean Sea, the average maximum body weight of fish is expected to shrink by 4% to 49% from 2000 to 2050 (Cheung et al. 2013).

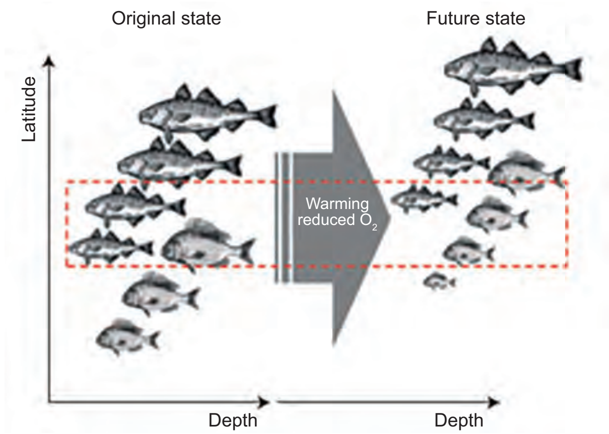


*Figure 1*
*Expected changes in body size at individual and assemblage levels. According to Cheung et al. (2013), due to the invasion/increased abundance of smaller-bodied species and local extinction/decreased abundance of larger-bodied species, the mean maximum body weight is expected to decrease at the assemblage level, with a vertical distribution shift of species.*

Despite relative local heterogeneity, the projected decrease in fish size is largest in the western Mediterranean (20%-49%). In contrast, the mean assemblage body weight is expected to increase in the Gulf of Lion likely due to the northward migration of large exploited species. However, interpreting global scale simulation results at a regional scale can be hazardous and more dedicated fine scale regional studies are needed. Nonetheless, changes in assemblage-level body size structure suggest that climate and ocean changes will cause dramatic modifications of food web dynamics (predator-prey interactions are strongly dependent on size as well as on food consumption rates), the natural mortality rate of fish populations (negatively correlated with maximum body weight) and size at maturity (positively correlated with maximum body weight) (Pauly 1980, Palomares & Pauly 1998, Cheung et al. 2013). Fishes in warmer waters are expected to have a smaller maximum body size and smaller size at first maturity with possible higher natural mortality rates (Sumaila et al. 2011). All these key population parameters determine population dynamics and productivity.

# Sea warming changes fish distribution and associated assemblages

In the Mediterranean Sea, the increasing abundance of thermophilic biota can be described by two major processes of change involving both indigenous and non-indigenous species (Boero et al. 2008): the northward extension and enhancement of native thermophilic species (i.e. meridionalization) and the increasing introductions and range extension of thermophilic non-indigenous species (i.e. tropicalization).

Due to seawater warming, numerous native thermophilic species have greatly extended their distribution range and are becoming more abundant especially in the northwestern part of the basin (box 1). One of the best studied case is the ornate wrasse *Thalassoma pavo*, a species once confined to the southern parts of the Mediterranean Sea, which penetrated into the Ligurian Sea in the 1980s, where it is now able to reproduce, thereby becoming "naturalized" (Sara et al. 2005, Bianchi 2007). *Sparisoma cretense*, a parrotfish species, is considered to be a clear indicator of meridionalization because of its increasing abundance over the last two decades (Azzurro et al. 2011). Originally, this parrotfish was thought to be common in the strait of Sicily (i.e. chiefly distributed along the southern and eastern coasts) but absent from northern Sicily. Several recent studies confirmed the increase in the populations of *Sparisoma cretense* over the last 10 years. Currently, the species is well established along the coast of France and in the central and northern Adriatic (Azzurro et al. 2011).

**Box 1**

**The effects of climate change on the Catalan Sea ecosystem**

The Catalan Sea represents a portion of the Western Mediterranean region and is located between the Balearic Islands to the east and the eastern Iberian Peninsula to the west (Figure B1a).

The region has shown clear signs of climate change, including an increase in sea surface temperature (SST) of approximately 1.1 °C in the last 40 years (Figure B1b), an increase in salinization of the intermediate and deep waters, a rise in sea level over the last century, and strengthening of seasonal stratification in summer (Calvo et al. 2011). A decrease in rainfall and wind, warmer surface waters and hence a longer stratification period is foreseen (Calvo et al. 2011).

The effects of climate change can be clearly seen in all the compartments of the marine ecosystem in the region. There has been an increase in thermophilic species, which are favored by increasing temperatures, in contrast to temperate species. These increases include algal, invertebrate and vertebrate species. For example, an increase in the SST has been linked with the expansion of round sardinella (*Sardinella aurita*) (Sabates et al. 2006), and with the decline of sardine (*Sardina pilchardus*) (Palomera et al. 2007). Declines in freshwater inputs and winds may have had an impact on pelagic fish species (Lloret et al. 2004).

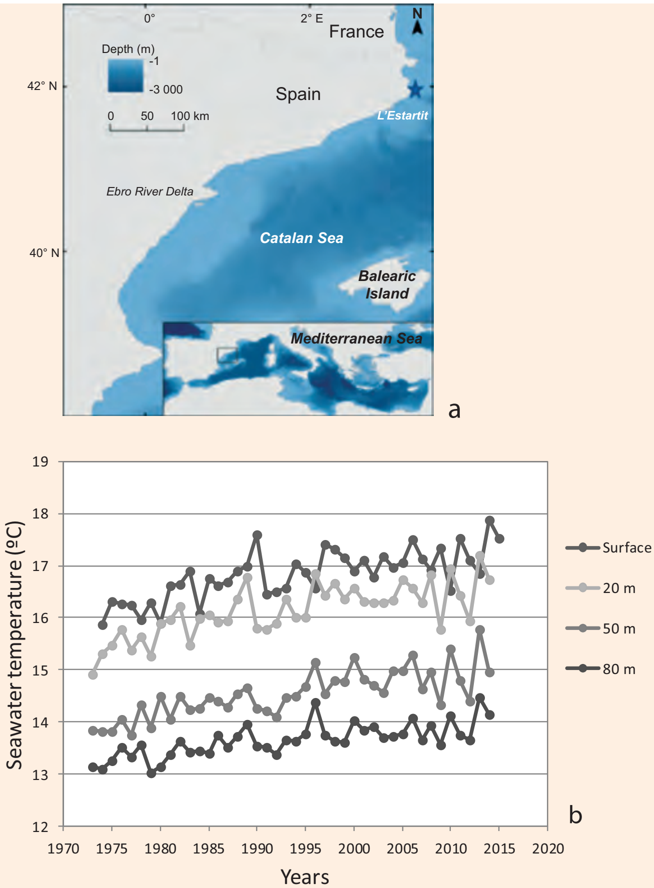


*Figure B1*

*a) The Catalan Sea region in the western Mediterranean Sea. Star: Estartit oceanographic station.*
*b) Evolution of the mean annual sea temperature at Estartit station from 1974 to 2015.*
*The curves present data at the surface, 20, 50 and 80 m depth, respectively.*
*Data source: Josep Pasqual in collaboration with the Institut de Ciències del Mar (ICM-CSIC), Barcelona, and Parc Natural del Montgrí, Les Illes Medes i el Baix Ter.*

Mass mortality events of sessile invertebrate species have been linked with anomalous warm waters in specific hot years with longer stratification periods (Coma et al. 2009). Significant mortality episodes have been documented for gorgonian and sponge species, which are long-lived and slow growing vulnerable organisms (Garrabou et al. 2009). In addition, the capacity of the ocean to absorb atmospheric CO2 has been linked with increased acidification of the seawater, which can have negative impacts on many pelagic and benthic organisms with calcareous body parts such as corals, mussels, pteropods and coccolithophores (CIESM 2008).

The strengthening of the stratification period of the water column has been linked with changes in primary productivity and with the increase in the smallest phytoplankton species (Calvo et al. 2011). The longer stratification period and the high SST has also been linked with more frequent and abundant proliferations of gelatinous species, including jellyfish (Molinero et al. 2008).

These effects have had marked impacts on food webs in the Catalan Sea, which occur simultaneously with other coastal anthropogenic effects such as overfishing, habitat degradation and pollution (Coll et al. 2010) and can have synergistic impacts (Calvo et al. 2011).

The barracuda *Sphyraena viridensis* and the dolphinfish *Coryphaena hippurus* are two other good examples of the meridionalization process. These two top predator species have greatly extended their natural distribution range over the last 30 years (Lejeusne et al. 2010, Azzurro et al. 2011). Due to the range expansion of these species, besides changes in fish species richness, a recent study predicts that under climate change the mean body size of fish assemblages will increase on the continental shelf with potential effects on trophic functioning (Albouy et al. 2013). However, this study only took distribution range shifts into account, but not the climate-induced physiological changes.

Most of the non-indigenous species in the Mediterranean Sea are thermophilic species originating from the tropical Indo-Pacific region (i.e. Lessespsian migrations). In total, more than 900 alien species have been recorded (Zenetos et al. 2012) and the introduction of warm and tropical alien species has been exacerbated by the warming of the eastern Mediterranean (Raitsos et al. 2010), which creates maritime corridors (box 2). Since 2011, the number of alien macrophyte, mollusk and polychaetes species has increased by two to three species per year, by three to four species per year of crustaceans, and by six species per year of fish (Zenetos et al. 2012). At the same time, the diversity of alien species is largely underestimated due to a "shifting baseline syndrome" (i.e. cultural traditions tend to embrace newly introduced organisms progressively, by attributing to them the values originally associated with native species. The new species are therefore included in the assumed normal or desirable state of a natural system) (Clavero 2014). Thus, the tropicalization of the Mediterranean Sea (i.e. the increased occurrence of warm-water biota), particularly in the eastern Mediterranean, seems inevitable (Bianchi & Morri 2003, Ben Rais Lasram & Mouillot 2009). This phenomenon may locally and temporally increase species richness but several studies demonstrated that warming and aquatic invasions can lead to the decline and even collapse of several marine populations (Bianchi & Morri 2003, Occhipinti-Ambrogi 2007). In the short to medium term, invasive aliens may cause major shifts in community composition and lead to a significant loss in Mediterranean biodiversity and, possibly, to cascade effects on food webs (Galil 2000, Streftaris & Zenetos 2006, Molnar et al. 2008, Lejeusne et al. 2010, Zenetos et al. 2012). Evidence for geographical extension is particularly abundant for species coming from the Red Sea (Azzurro et al. 2008). For instance, the bluespotted cornetfish, *Fistularia commersonii*, which was observed for the first time in 2000 in Israel, was soon afterwards recorded all over the eastern and central Mediterranean coasts, up to the proximity of the Strait of Gibraltar (Golani 2000, Bilecenoglu et al. 2002, Pais et al. 2007, Azzurro et al. 2008, Dulčić et al. 2008). Today, it is one of the most successful invaders of the Mediterranean Sea and can have strong potential impacts on food web dynamics by preying upon commercially important fish such as the bogue (*Boops boops*) and the red mullet (*Mullus barbatus*) and by competing for food with native piscivorous fish (Kalogirou et al. 2007).

## Box 2
## Climate change and exotic fish invasions

**Does climate play a key role in the dispersal success of exotic fish species?**

The invasion success of some exotic species has been shown to be positively related to the match between native and colonized environments (Duncan et al. 2001). In particular, a species that is introduced in similar thermal conditions is more likely to establish successfully. This is called the "climate match" hypothesis, and it appears to play a key role in the invasion rate in the Mediterranean Sea. The greater dispersal success of Lessepsian species was associated with thermal conditions prior to 1980 (Ben Rais Lasram et al. 2008); crossing the Suez Canal does not necessarily guarantee successful invasion and widespread dispersal of fish populations.

**Is the Mediterranean Sea experiencing increasing southern invasions?**

Many species have shifted their distribution area by extending northward as a response to climate warming (Cheung et al. 2009). Southern invasions are an indicator of the impact of climate change on biodiversity. Lessepsian species migrating through the Suez Canal inevitably originate from more southern latitudes than the Mediterranean Sea, so their dynamics can be easily correlated to climate warming.

In contrast to the Lessepsian species, Atlantic species do not come necessarily from lower latitudes. Their introduction rate assessed by the number of species that migrated to the Mediterranean Sea, does not therefore indicate whether southern migrations are accelerating during a period of global warming. The original latitude of introduced Atlantic species rather than their abundance can be used as an indicator of the rate of southern invasions. Ben Rais Lasram and Mouillot (2009) showed that the Lessepsian invasion rate and the latitude of Atlantic species entering the Mediterranean Sea both significantly correlated to the Mediterranean SST, positively and negatively respectively. These analyses suggest that southern invasions from the Red Sea and from the Atlantic accelerate with global warming (Figure B2).

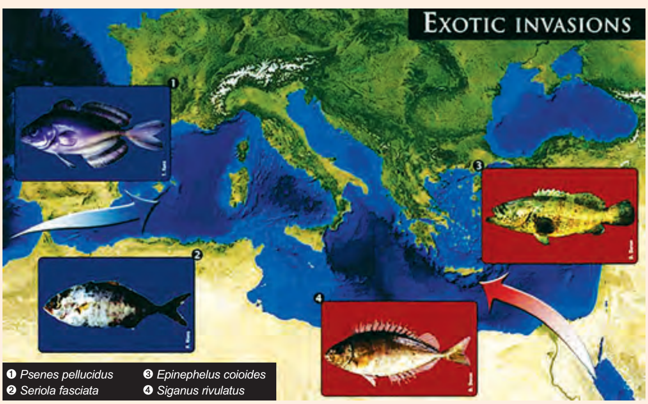


*Figure B2*
*The Mediterranean Sea under southern invasions.*

**Is there an increasing spatial overlap between exotic and endemic Mediterranean fish fauna?**
Spatial overlap is an indicator of the intensity of interaction between species and the potential hazards coming from exotic species. By comparing the distributions of endemic and exotic species, it appeared that between 1980 and 2006, major exotic species have moved northwards in the Mediterranean Sea by approximately 300 km (Ben Rais Lasram and Mouillot 2009). After the 1980s, some exotic fish species reached the coldest areas of the Mediterranean Sea (western basin), for example the Adriatic Sea, which is a major hotspot of endemism. The number of exotic species in the Mediterranean is now 98.4% higher than it was 20 years ago (Ben Rais Lasram and Mouillot 2009).

**What can we learn from the spread of Lessepsian species?**
Species move to keep pace with changing climates, but can they move at the required speed? The spread rates of native species may underestimate how fast species can move. The exceptional spread rates of Lessepsian species can give upper estimates to the rate at which native species could spread to colonize suitable habitats under climate change. Hiddink et al. (2012) estimated that about 20% of Lessepsian species could not spread fast enough to keep pace with climate change in about 20% of the global seas, thus suggesting that climate change may lead to biodiversity loss.

**Can we predict invasion risk in the Mediterranean Sea?**
Species Distribution Models (SDM) have been used intensively to predict range shifts of marine species in the context of climate change (Cheung et al. 2009; Albouy et al. 2013). Parravicini et al. (2015) showed that Lessepsian fish species may spread far beyond their native niches and that SDMs do not predict their new distributions better than null models. This suggests that SDMs may underestimate the potential spread of Lessepsian species.

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In the Mediterranean Sea, the history of the invasive of the rabbitfish species *Siganus luridus* and *Siganus rivulatus*, two herbivorous fishes, is probably the best example of impacts caused by invasive alien species on the whole ecosystem, from primary producers to top predators (Galil 2007). For instance, a survey conducted along around 1,000 km of coastline (temperate reefs) in the eastern Mediterranean demonstrated that, in regions with abundant rabbitfish, canopy algae were 65% less abundant, there was a 60% reduction in overall benthic biomass (algae and invertebrates) and a 40% reduction in total species richness (Vergés et al. 2014) (Figure 2).

Therefore, climate warming produces "winners" and "losers" among fish assemblages. Winner species may enjoy higher survival, growth and reproduction

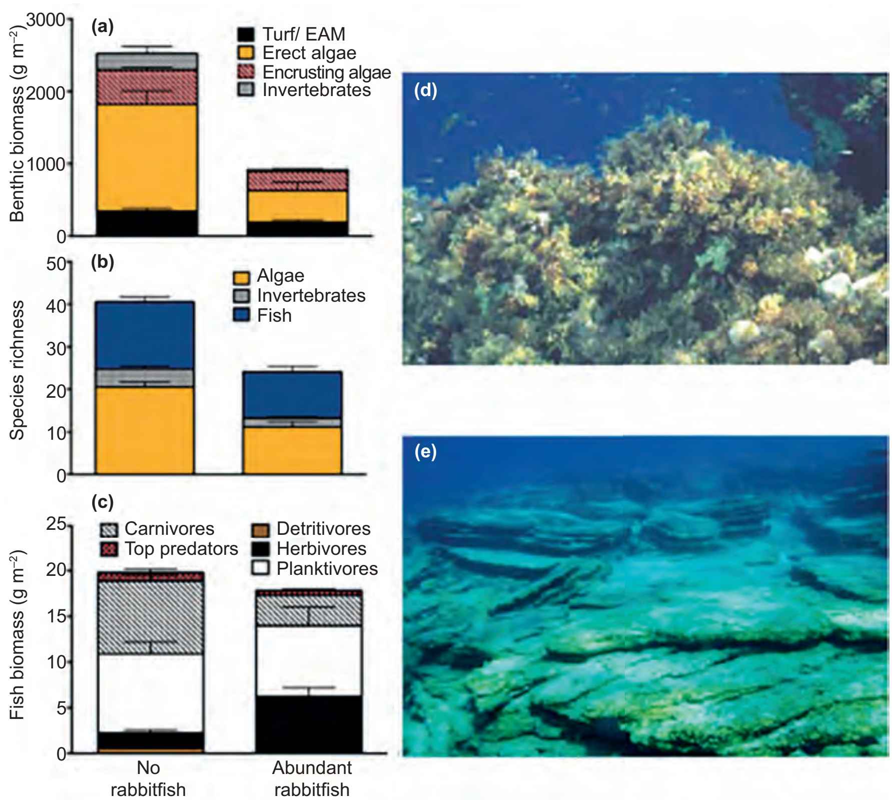



*Figure 2*
*Benthic biomass and species richness patterns in Mediterranean regions with or without rabbitfish. (a) Total biomass of dominant benthic organisms; (b) Total species richness of algae, invertebrates and fish; (c) Fish biomass of major trophic groups; (d) Photo of a Cystoseira spp. forest where tropical rabbitfishes are absent; (e) Barren area typical of the eastern Mediterranean sites where range-shifting tropical rabbitfish are abundant.*
*From Vergés et al. (2014).*

rates in a changing Mediterranean while for losers, more stressful conditions may lead to higher mortality rates, reduced growth, smaller size and reduced reproduction (Doney et al. 2012). For winners, climate warming is synonymous with geographic range extensions (e.g. ornate wrasse has increased its range by about 1,000 km in recent decades) while for others it is synonymous with range contraction. This is particularly true for cold-water species. Projecting the potential future distributions of 75 Mediterranean endemic fish species based on a global warming scenario implemented with the OPAMED8 model and Ecological Niche Models (ENMs), Ben Rais Lasram et al. (2010) showed that, by 2041-2060, 25 species would qualify for the IUCN (International Union for the Conservation of Nature and Natural Resources) Red List and six species would become extinct (for example, starry sturgeon *Acipenser stellatus* and European sturgeon *Huso huso*). For "narrow" endemic species (i.e. endemic species found strictly in the Mediterranean Sea that do not reach the neighboring Atlantic Ocean and Black Sea) their extinction would be irreversible.

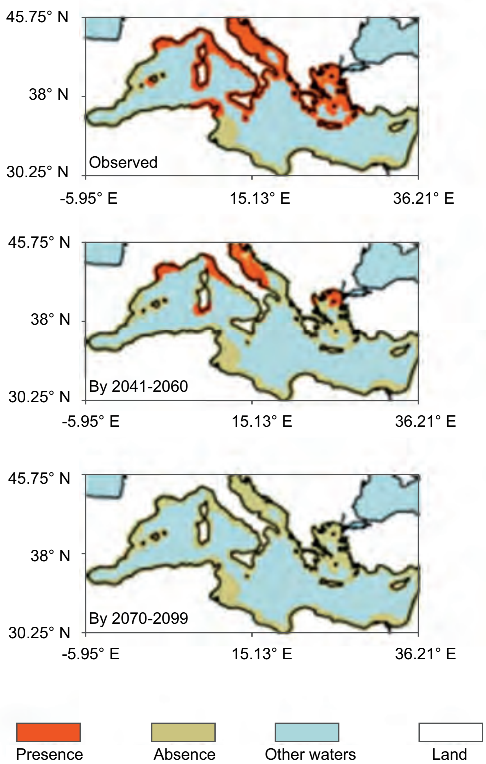



*Figure 3*
*Observed distribution areas of the endemic Mediterranean fish* Gobius geniporus *(1980s, top) and projected potential future thermal habitats (by 2040-2060 middle; 2070-2099, bottom). The "cul-de-sac" effect is clearly visible for this species. From Ben Rais Lasram et al. (2010).*

## Box 3
## Climate change impacts on the Gulf of Gabes ecosystem

The Gulf of Gabes is located in southern Tunisia, at the junction of the eastern and the western basins. It is the second largest continental shelf in the Mediterranean Sea (36 000 km²) after the Adriatic Sea. The seabed is covered by an extensive *Posidonia oceanica* meadow, the largest in the Mediterranean Sea and one of the largest in the world (Batisse & Jeudy de Grissac 1998). The meadow is a spawning ground for marine organisms and an important nursery for juvenile fish of the region (Hattour et al. 1995), it hosts 247 of the 327 marine fish species of Tunisia of which 44 species have only been recorded in the Gulf of Gabes (Bradai et al. 2004).

The high diversity and production of the Gulf of Gabes and its accessibility (very shallow slope of the continental shelf, soft bottom suitable for bottom trawling) have contributed to a considerable increase in the number of fishing fleets. The Gulf of Gabes has become the main fishing area in Tunisia.

Like the rest of the Mediterranean Sea, the Gulf of Gabes has been undergoing warming: sea surface temperature and salinity have increased by respectively 2 °C and 0.5 over the last 100 years. The warming of the surface layer has resulted in intensification of the thermohaline circulation, and variations in water density have led to a rise in sea level of 1 cm over the last century (Ben Mahmoud & Harzallah 2009).

Climate change has likely caused the observed shifts of the distribution areas of some fish species usually encountered in northern Tunisia: *Brama brama*, *Trachinotus ovatus*, *Ariosoma balearicum* and *Oblada melanura* currently inhabit the Gulf of Gabes (Bradai & Capapé 2001). In parallel, the colonization of the waters by some exotic thermophilic species has also been attributed to climate change (e.g. Missaoui & Zaouali 1995, Bradai et al. 2004). The fish species exploited in this coastal region of Tunisia are also strongly impacted by climate change. Species distribution models that include habitat selection processes and the physiological temperature tolerance of exploited marine species, project a decline in species prevalence by an average of 56% by the end of the 21st century (figure B3). The models suggest that the magnitude of the changes caused by climate will be greater than that caused by the loss of the *Posidonia* meadow. This suggests that climate, and particularly temperature, is a key driver of marine species distribution even at a small spatial scale like the Gulf of Gabes (Hattab et al. 2014).

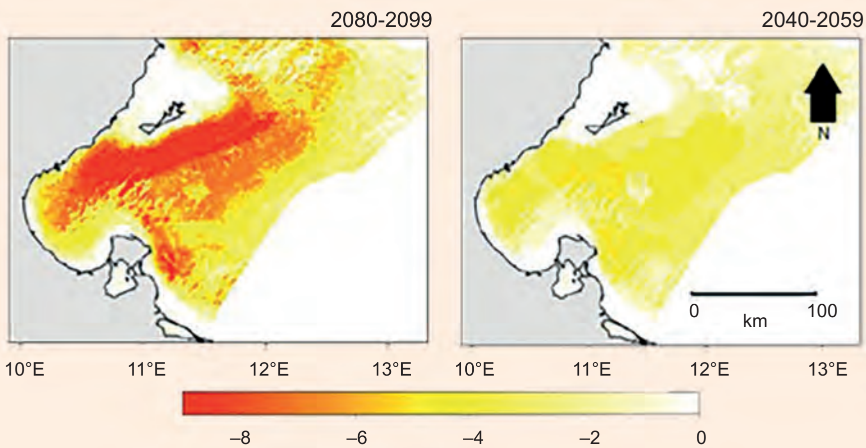



*Figure B3 Differences between species richness predicted under current climate conditions (1982-2009, baseline scenario) and values predicted under a mid-century climate scenario (2040-2059, right panel) and an end-century climate scenario (2080-2099, left panel) (Hattab et al. 2014).*

In addition, the ENMs showed that by the middle of the 21st century, the coldest areas of the Mediterranean Sea (i.e. Adriatic Sea and Gulf of Lion) would act as a refuge for cold water species. However, by the end of the century, those areas are projected to become a "cul-de-sac" that would drive these species towards extinction. By 2041-2060, 31 species were projected to extend their geographic range, whereas the geographic range of 44 species was projected to contract (e.g. the slender goby *Gobius geniporus*) (Figure 3). The Gulf of Gabes, one of the largest continental shelves in the Mediterranean Sea and a major area of fishing activities is also undergoing a warming phase with marked consequences for the distribution of exploited species (box 3).

Overall, 25% of the Mediterranean continental shelf is predicted to be subject to a total modification of endemic assemblages by the end of the 21st century (Ben Rais Lasram et al. 2010). This projection are likely to be conservative. A more recent study based on the SRES IPCC A2 ("*business as usual*") scenario suggested that at the end of the century, 54 species (mainly gobiidae) will have lost their climatically suitable habitat (Albouy et al. 2013); species richness is predicted to decrease across 70.4% of the continental shelf area (Figure 4) and mean fish body size to increase over 74.8% of the area. Thus, by reducing the geographic range size of small-bodied species, climate change may contribute to the loss of small and low trophic level fishes, which may have ecosystem-wide impacts (Albouy et al. 2013). This last projection disagrees with projections of Cheung et al. (2013) who rather suggested that maximum body weight will decrease at the scale of the Mediterranean basin. However, contrary to Cheung et al. (2013), Albouy et al. (2013) only considered distribution shifts caused by climate warming and not the resulting physiological changes, thus introducing a source of structural uncertainty.

For two exploited species, the allis shad *Alosa alosa* and *Microchirus azevian*, projections highlight possible extinction strengthened by exploitation by fisheries. Other commercially important species such as the European flounder (*Platichtys flesus*), the Danube sturgeon (*Acipenser gueldenstaedtii*) and the starry sturgeon (*Acipenser stellatus*) are likely to be affected by climatic change both in fresh-water and marine habitats. Because marine species track their climate niches from the different parts of the Mediterranean, Albouy et al. (2012) showed that most of the Aegean and Adriatic Sea will be subject to a high rate of species replacement and an increase in species richness by the mid-21st century, as a result of a northward and eastward shift in species ranges. However, by the end of 21st century, with increasing temperature, these same areas, along with the Gulf of Lion, are expected to undergo a net decrease in species richness. The "cul-de-sac effect" described by Ben Rais Lasram (2010) suggests that for many fish species, the loss of their thermal niche may not be compensated for by the arrival of other species from the south (Albouy et al. 2012).

Beyond consequences at the level of individual species, changes in fish distributional range may result in dramatic changes in the structure of the community and of the food web, with potential consequences for ecosystem

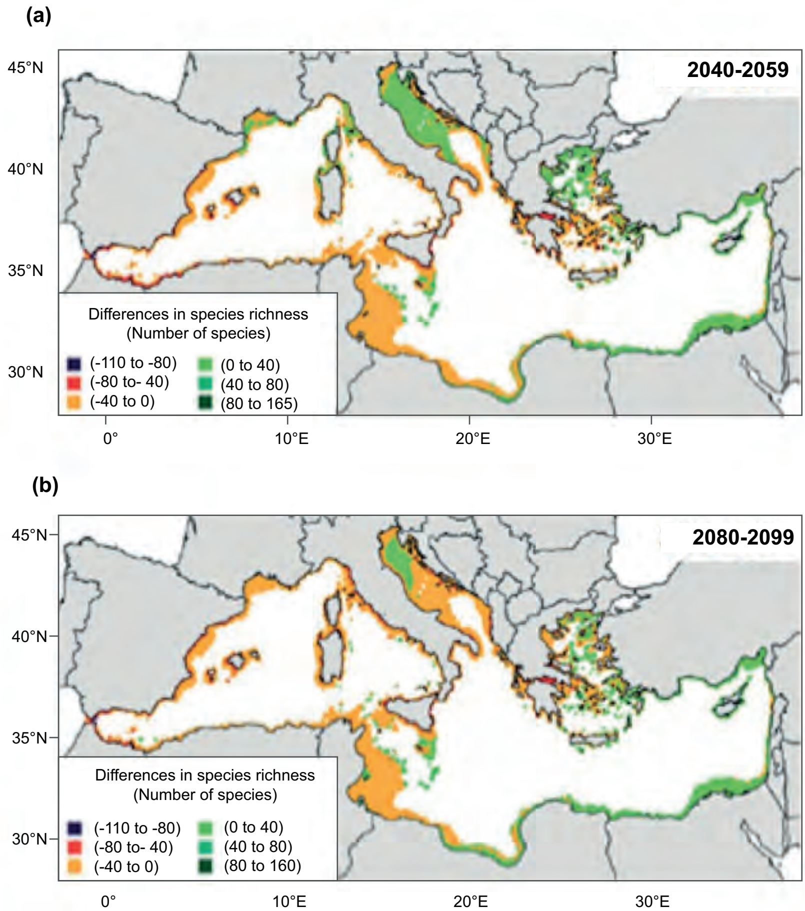



*Figure 4*
*Differences in species richness between a baseline scenario (1961-1980) and two time periods (a: 2040-2059 ; b: 2080-2099) predicted for the continental shelf of the Mediterranean Sea (all fish species of the continental shelf are represented) according to the SRES IPCC A2 scenario. Adapted from Albouy et al. (2013).*

functioning. To capture this phenonemon, Albouy et al. (2014) built a trophic size-based model coupled with current and projected future distributions of Mediterranean fish species. These authors showed that by 2080-2099, 54 fish species among 256 coastal endemic and native species included in the model, would disappear from the Mediterranean continental shelf, resulting in a widespread decrease in local species richness. These disappearances will likely be accompanied by a decrease in the number of trophic links between the fish species (in the order of 70%) of the continental shelf. Moreover, fish prey abundance is expected to be lower at the end of the 21st century compared to the baseline period (1961-1980), which may further increase the probability of extinction of fish species (Albouy et al. 2014). Projecting species distribution in the future is a simple way to address the effects of climate change on fish communities, but ignores changes in substrates and in physical habitats, for example. The potential impact of climate change on some essential habitats could severely affect the life cycle and the spatial distribution or redistribution of numerous marine species whether indigenous or not (box 4).

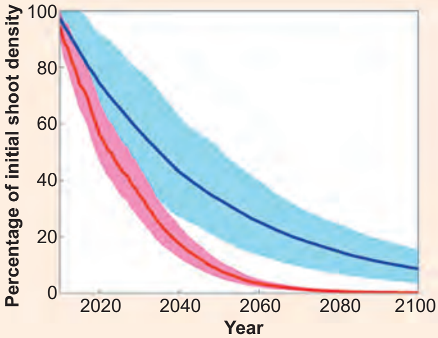


## Climate Change affects migration patterns and phenologies

Climate influences a variety of ecological processes such as migration patterns and phenologies (Stenseth et al. 2002). Several studies have shown that climate driven changes in temperature modify or will modify the phenology of annual migrations to feeding and/or spawning grounds (e.g. Sims et al. 2004, Huse & Ellingsen 2008, Rijnsdorp et al. 2009). For instance, based on a review of published data in the northeast Atlantic, Rijnsdorp et al. (2009) reported that pelagic species exhibit clear changes in seasonal migration related to climate-induced changes in secondary production. In the Mediterranean Sea, climate change and variability are critical to the seasonal spawning and migration behaviors of the Atlantic Bluefin tuna *Thunnus thynnus*, a large migratory fish species of high economic and ecological importance (Ravier & Fromentin 2004, Muhling et al. 2011). Indeed, it has been suggested that water temperature triggers the spawning activity of the species (Muhling et al. 2011). If the Mediterranean Sea warms up earlier in the year, spawning may also start earlier, with a potential mismatch between favorable feeding conditions and tuna reproduction. In addition, the migration patterns and spatial distribution of highly mobile large pelagic fish, such as bluefin tuna, may be indirectly altered by climate-induced changes in prey abundance (Walther et al. 2002). Historical data from the Mediterranean Sea suggest that bluefin tuna may change their migration routes and spawning behaviors in association with long-term fluctuations in temperature (Ravier & Fromentin 2004). As a result, the migration routes of bluefin tuna may vary and adapt to climate change and potentially explore new spawning grounds in the Atlantic. However, some authors have also warned that overfishing has likely reduced the genetic diversity of the bluefin tuna, so its ability to adapt to climate change may also be affected (Perry et al. 2010, Planque et al. 2010, Muhling et al. 2011). Moreover, the energy cost and potential reduced fitness resulting from adaptation to a changing climate may reduce the surplus production of exploited stocks and make them more vulnerable to previously sustainable fishing levels (Brander 2010). This assumption applies to all exploited fish populations that experience high and prolonged fishing mortality and consequently a selective pressure of several alleles and genotypes. In fact, the loss of sub-populations may reduce the ability of marine species to adapt to climate change (Brander

## Box 4
## Climate change will impact essential fish habitats

Climate change reduces habitat complexity and has likely the most pronounced influence on habitat-forming species such as seagrass (Hoegh-Guldberg & Bruno 2010). A recent study projected the trajectory of *Posidonia oceanica* meadows under expected sea warming in the western Mediterranean over the 21$^{st}$ century and concluded that warming could lead to the functional extinction of *P. oceanica* meadows by the middle of this century even under a low greenhouse-gas emissions scenario (Jordà et al. 2012) (Figure B4).



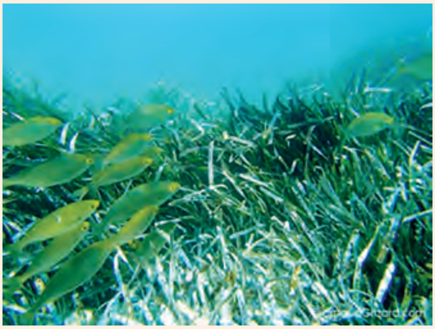


**Figure B4**
***Left*: percentage of P. oceanica shoot density in the twenty-first century. The pink line represents the projected percentage of shoot density under warming and local impacts, and the blue line represents the projected trend in the absence of warming. From Jordà et al. (2012). *Right*: photo of P. oceanica. Source www.arnaudgrizard.com.**

Given the importance of the functional role of seagrass meadows in the ecosystem (as an essential habitat for commercially and recreationally important fishery species, coastal protection from erosion, as a food source for megaherbivores such as sea turtles, nutrient recycling, etc.), the degradation of this key habitat may have dramatic consequences for regional biodiversity, food web dynamics and *de facto* for human welfare (Beck et al. 2001, Orth et al. 2006, Waycott et al. 2009, Jordà et al. 2012). In addition, Hattab et al. (2014) showed that the habitat loss of *P. oceanica* in the Gulf of Gabes, replaced by muddy sand, combined with climate change, triggered a high level of species replacement and a significant reduction in the geographical range of several species including the bluespotted seabream *Pagrus caeruleosticus*, the speckled shrimp *Metapenaeus Monoceros* and the brown comber *Serranus hepatus*, and that these species might be replaced by other commercial species such as the black goby (*Gobius niger*), the European hake (*Merluccius merluccius*), and the musky octopus (*Eledone moschata*) (Hattab, et al. 2014). Organisms typically respond to climate change by shifting their biogeographic ranges to maintain their thermal regime (Parmesan & Yohe 2003). However, a recent analysis of the velocity of climate change, as the rate of poleward migration of isotherms with climate change, identified the Mediterranean Sea as a region of concern because the northward displacement of the biogeographic ranges of endemic species, such as *P. oceanica*, is bounded by the presence of the European continent (Burrows et al. 2011).

In addition to sea warming, ocean acidification (OA) is considered as a major threat to the marine environment in the coming years. Calcifying organisms can be affected by increased seawater acidification, which both reduces the growth of calcareous skeletons and tends to dissolve them (Bramanti et al. 2013). Habitat-forming species such as *Lithophyllum cabiochae* (a crustose coralline alga which constitutes marl beds) could be severely affected by OA. As marl beds are spatially complex habitats that provide shelter for numerous species and trophic groups (Barbera et al. 2003), OA could have major consequences for the biodiversity and biogeochemistry of coralligenous communities (Martin & Gattuso 2009).

2010, Planque et al. 2010). By influencing food abundance and age structure, climate and fishing may also have significant effects on migration route fidelity, population resilience, and colonization of new habitats (Perry et al. 2010).

With this synthesis, we highlight the observed and potential consequences of climate change at different levels, from the individual to the ecosystem level. Climate change is expected to affect the physiology of individuals with consequences for community assemblages and population dynamics. Meridionalization and tropicalization processes have already taken place but appear to have accelerated in recent years with dramatic consequences for the Mediterranean biodiversity in the medium and long term. For several species, in particular those of commercial interest, climate change is expected to modify migration patterns and periodicities with consequences for population dynamics and fisheries management. All these changes are shaping a different Mediterranean Sea in which living resources and human activities will need to adapt in a sustainable way.

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# Climate change and fisheries

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There is considerable evidence that Mediterranean marine species have been shifting their ranges, migration patterns, seasonal activities and periodicities, abundances, growth and mortality rates, and consequently their trophic interactions in response to climate change and variability. These responses may ultimately have significant consequences for ecosystem productivity, biodiversity and functioning and hence for the overall goods and ecosystem services they provide, especially the production of living resources (Kirby & Beaugrand 2009, Doney et al. 2012).

Climate change is an additional pressure on marine ecosystems that are already subject to many anthropogenic disturbances such as fishing activities. This is especially true in the Mediterranean Sea, where a series of human impacts co-occur and interact (Coll et al. 2010, Micheli, Halpern, et al. 2013). The consequences of climate change for marine resources need to be evaluated in this context and research and management need to take interactions between fishing, other human impacts, and climate into account (Brander 2010, Perry et al. 2010). This chapter thus has three aims: (i) to investigate the synergy between climate and fishing (a major human impact on Mediterranean marine ecosystems) and, using some examples from the Mediterranean Sea, to highlight how these two factors interact, from the individual to the ecosystem scale, (ii) to assess and quantify the consequences of climate change for the composition of fishery catches in the Mediterranean Sea, and (iii) to address the consequences of climate change for the management tools and strategies implemented in the region.

## Fishing and climate act in synergy

Studies that specifically assess the synergistic effects of both climate change and fishing on fish resources and ecosystem functioning in the Mediterranean Sea are rare. However, studies conducted in other regions or at global scale describe a range of changes that can be expected in the Mediterranean. Under climate change, fishing is likely the most significant anthropogenic impact on marine fishes. Fishing has been going on in the Mediterranean Sea for a thousand years and has resulted in overexploitation of the main commercial species, with no less than 90% of stocks assessed in 2015 categorized as overfished (STECF 2016). Fishing does not only reduce the abundance and production of fish populations but also results in changes in their population structure (e.g. by truncating the demographic structure with fewer older fish and by altering life history traits such as mean body size and age at maturity) and in species composition (e.g. by removing populations of large sized fish) (Colloca et al. 2013). In an ecosystem context, where inter- and intra-specific interactions are the main drivers of community structure, fishing exerts direct pressure on the main target species but also indirectly affects their competitors, prey and predators, thereby potentially affecting the whole food web (Scheffer et al. 2005, Daskalov et al. 2007, Coll et al. 2008). In addition to reducing the size of target populations, one direct impact of fishing is simplifying the demographic structure of marine populations, making them more sensitive to climate variability at interannual to interdecadal scales (Perry et al. 2010). Fishing of finfishes and invertebrates can reduce the number of age groups in populations, lead to spatial contraction, sometimes to a loss of population sub-units, and alter life-history traits such as age at maturity and longevity (Perry et al. 2010, Planque et al. 2010). All these effects may make populations more susceptible to climate variability at different temporal scales. For instance in the Mediterranean Sea, Hidalgo et al. (2011) showed that the long-term exploitation pattern has likely eroded the age structure of hake (*Merluccius merluccius*), one of the main commercially exploited species. Hake subsequently became more recruitment-dependent, and thereby more sensitive to climate variability (Figure 1). This phenomenon is called the "age truncation effect" (Hsieh et al. 2006).

In the same way, Ottersen et al. (2006) demonstrated that heavily fished stocks were subject to more pronounced variability in recruitment linked to environmental fluctuations, due to changes in the spawning stock age and size composition. Hsieh et al. (2006) showed that exploited species exhibit higher temporal variability in abundance than unexploited species. Indeed, truncation of the age structure caused by fishing may reduce the capacity of exploited populations to buffer environmental events, especially anomaly events. Fishing can thus cause higher fluctuations in the abundance of commercially targeted species thereby increasing the risk of collapse of a heavily fished population from stochastic environmental events (Scheffer et al. 2001, Hsieh et al. 2006). Fluctuations in fish stocks may have consequences for both ecosystem functioning and fishing sustainability. In addition, fishing communities that depend on just a few local species have become more vulnerable to fluctuations in stocks, whether due to overfishing or climate variability (Brander 2010).

Under fishing pressure, the mean turnover rate of fish communities is expected to increase due to a relative increase in the proportion of smaller individuals with higher metabolic rates and to the depletion of the major predatory demersal fish resources that have a lower turnover rate (Myers & Worm 2003). In this

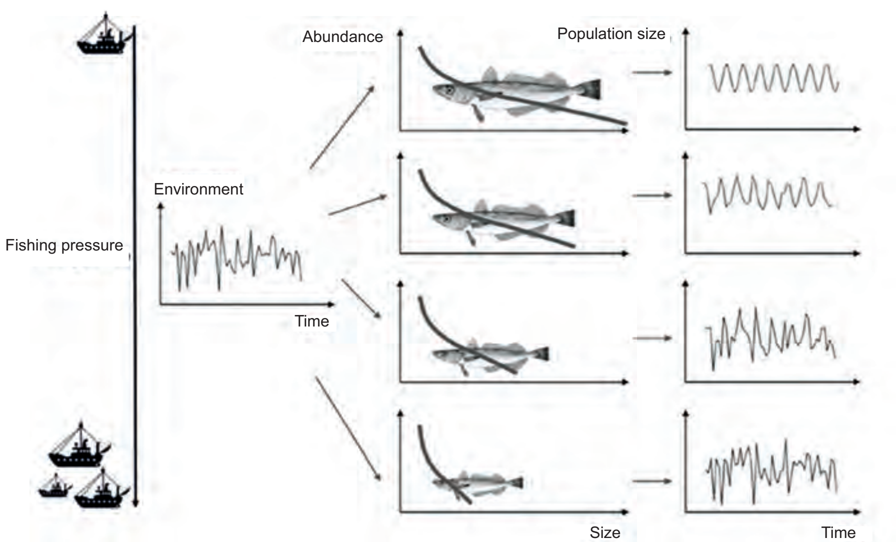


*Figure 1*
*According to Hidalgo et al. (2011), fishing "by altering the demographic structure, populations switch from an internally-generated to an externally-forced fluctuation mode, tracking the environmental variability more closely".*
*Adapted from Hidalgo et al. (2011).*

context, Perry et al. (2010) pointed out that "*these changes are expected to alter how the community responds to climate forcing since exploited fish communities with faster mean turnover times are expected to track more closely the short-term variability in production that results from variability in climate*". In addition, by removing top predators and favoring the dominance of short-lived prey populations with rapid turnover rates, fishing modifies the trophic controls that drive ecosystem dynamics, i.e. generally weakening top-down control and strengthening bottom-up control, which can lead to much greater vulnerability of the marine system to climate forcing (Perry et al. 2010).

In view of the current state of fish stocks in the Mediterranean basin, climate change in the region will strongly affect marine resources with several ramifications in food webs dynamics and ecosystem functioning. The Mediterranean Sea, which for decades has been - and continues to be - subject to intense exploitation of marine resources, is likely to experience stronger bottom-up control. This will lead to greater vulnerability and variability of the system to climate forcing, with implications for fisheries sustainability and biodiversity conservation.



## Climate-induced changes in commercial catches

Worldwide, fisheries will be impacted by changes in the distribution and in the catches of exploited marine species (Cheung et al. 2008, 2016, Barange et al. 2014), which will affect the economics of fisheries worldwide (Sumaila et al. 2011). In the Mediterranean Sea, the change in fisheries catch potential is partly due to northward and eastward shifts in fish distribution (see sub-chapter 2.1.3) that result in the invasion of warmer-water species into higher latitudes (e.g. Adriatic Sea) and local extinction in the southern Mediterranean region. Thus, in the near future, species that are commercially important in some areas may no longer be available. This may be already the case of the once abundant sardine (*Sardina pilchardus*), which has decreased drastically in the northern Mediterranean Sea in the last decade (Palomera et al. 2007).

By 2050, under a high emission scenario (Representative Concentration pathway 8.5), Cheung et al. (2016) predicted an up to 5% reduction in the potential catches at the Mediterranean scale (Figure 2). Furthermore, when considering changes in biogeochemistry such as ocean acidification and reduction in oxygen concentration, these authors also predicted a decrease in fish growth performance, which, along with a higher rate of distributional shift, may reduce estimated catch potential (Cheung et al. 2011). Changes in phytoplankton community structure may even reduce the projected catch potential by a further 10% (Cheung et al. 2011).

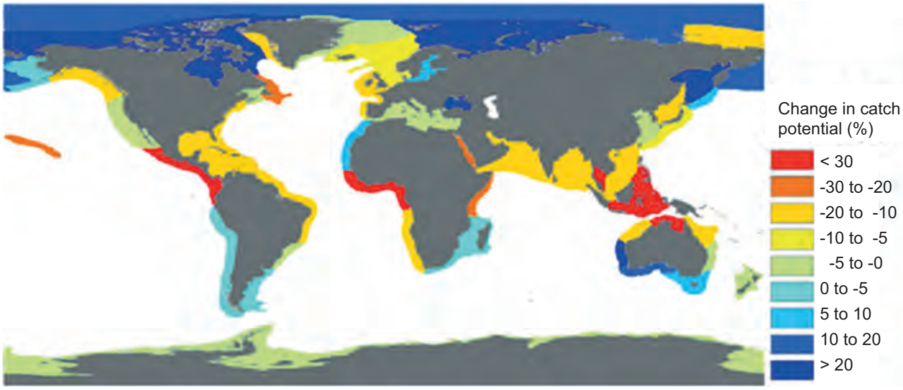


*Figure 2*
*Mean percentage changes in potential catch by 2050 relative to present day, under the RCP 8.5 scenario. From Cheung et al. (2016).*

This decrease in catch potential will be accompanied by tropicalization of the catch (i.e. an increase in warm-water species in catch composition). Indeed, Cheung et al. (2013) showed that in the Mediterranean Sea, the Mean Temperature of the Catch (MTC, i.e. the average inferred temperature preference of the exploited species weighted by their annual catch) has significantly increased since 1970, evidence for an increase in the catch of warmer water species and a decrease in the catch of colder water species. This index, which reflects changes in the composition of marine fisheries catch is closely linked to warming of the Mediterranean Sea. For the period 1970-2010, the MTC for the western, central and eastern Mediterranean has increased by 0.56 °C, 1.05 °C and 0.29 °C per decade, respectively (Tsikliras & Stergiou 2014) (figure 3). Moreover, if Lessespsian species are included, the MTC rate would be higher in all areas (Tsikliras & Stergiou 2014).

With the proliferation of non-indigenous invasive species (see sub-chapters 2.1.3), there is a need to explore market options for non-target species currently of low or no economic value. In general, changes in the composition of commercial fisheries catches have detrimental socioeconomic implications for fisheries, markets and consumers (Weatherdon et al. 2016). This is the case of the decline in small pelagic fish species (Van Beveren et al. 2016). However, climate change and the associated increase in sea surface temperature may offer opportunities to some Mediterranean fishermen to increase landings of tropical and subtropical species, some of which are of great commercial interest (e.g. the dolphinfish *Coryphaena hippurus*) (Weatherdon et al. 2016).

From qualitative and quantitative analyses of catch composition of a small tuna trap along the Ligurian coast, Cattaneo-Vietti et al. (2015) showed that in the last few decades there have been notable changes in species composition, with a decrease in the abundance of certain scombroids such as mackerel (e.g. *Scomber scombrus*) and bullet tuna (i.e. boreal species) and an increase in the abundance of carangids such as horse mackerel (*Trachurus* spp.) and amberjacks (e.g. *Seriola dumerili*) and other typical southern-water fish species (e.g. the dolphinfish *Coryphaena hippurus* and the east Atlantic barracuda *Sphyraena viridensis*). Using 'local ecological knowledge' (LEK), a recent study showed an increase in Carangidae and Sphyraenidae (thermophilic species) over time, but a simultaneous decrease in Scombridae and Clupeidae (Azzurro et al. 2011). In the western Mediterranean Sea, LEK information made it possible to record the proliferation of some species, including cephalopods, jellyfish and small-sized fish (Coll et al. 2014). These proliferations may be partly due to the impacts of fishing on the ecosystem and to climate change. Tzanatos et al. (2014) also demonstrated that fisheries landings showed significant year-to-year correlations with temperature for approximately 60% of 59 species. Based on these species, these authors showed that approximately 70% of landings were negatively correlated with temperature (e.g. hake, common sole, sardine and Norway lobster) and had decreased by an average of 44%. However, increasing trends were also found in the landings mainly for species with short life spans (e.g. anchovy, greater amberjack). Finally, Tzanatos et al. (2014) detected a shift in the landings of the 59 most important species/taxa indicating that most of them had undergone a significant abrupt change in the mid-late 1990s paralleling an increasing SST regime shift during the same period. For instance, a negative shift for hake and sardine has been reported along with a positive shift for anchovy (*Engraulis encrasicolus*) or white seabream (*Diplodus sargus*). In addition to northward migration, invasive and endemic populations respond to climate warming by bathymetric displacement. This is particularly true in the case of red mullet (*Mullus barbatus*), hake and spottail mantis shrimp (*Squilla mantis*), three species (local, native and indigenous, respectively) that have been reported to move into cooler and deeper waters to avoid warm-water competitors (Galil & Zenetos 2002). This shift in the distribution of stocks of exploited species is expected to affect their availability to fisheries and possibly to reduce commercial catches. Here, we mainly addressed the effects of warmer temperatures on fish resources and their fisheries, but a rise in CO2 levels also triggers ocean acidification and can affect Mediterranean fisheries. For example, sponge fisheries are seriously threatened by acidification of the sea because of the low capacity of most sponges for acid-base regulation (Linares et al. 2005, Goodwin et al. 2014). Ocean acidification is looked on as a major threat to the marine environment in the coming years and may have dramatic effects on calcifying organisms such as the precious Mediterranean red coral (*Corallium rubrum*), which is a long lived, slow growing gorgonian endemic species in the Mediterranean Sea. Sold at US$ 230-300 per kg, it is one of the most valuable corals thanks to its bright red durable skeleton used in the jewelry industry (Tsounis et al. 2010, Bramanti et al. 2013).

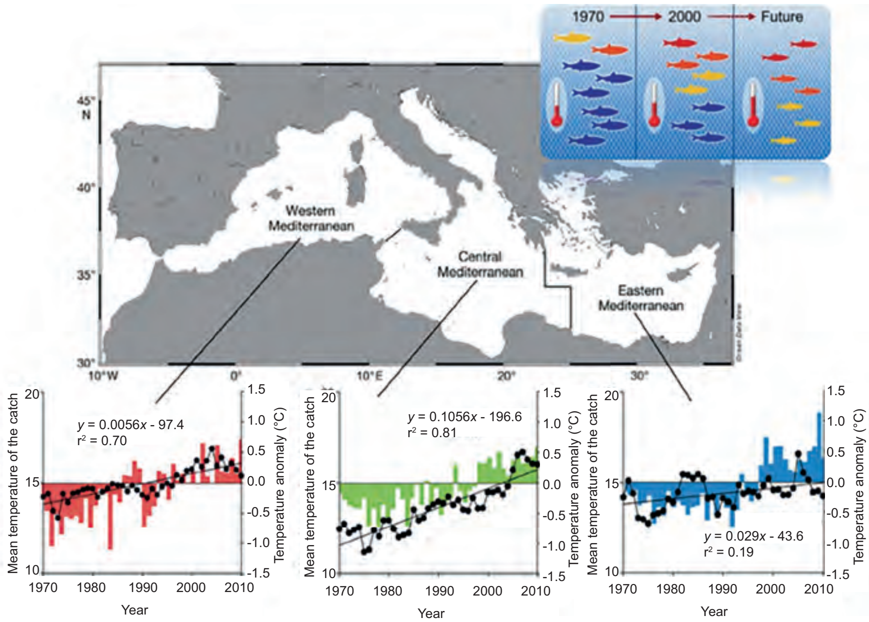


*Figure 3*
*Evolution of the mean temperature of the catch between 1970 and 2010*
*in the western, central and eastern Mediterranean Sea.*
*From Tsikliras & Stergiou (2014). The picture at the top right is from Cheung et al. (2013).*

# Adapting the whole management system

## Effectiveness of Marine Protected Areas

Marine protected areas (MPAs) are the flagship management tool for conserving biodiversity and ensuring sustainable ecosystem services (Garcia et al. 2013). The objective of creating MPAs is conserving sensitive habitats and associated species and biodiversity, while taking economic and social considerations into account. Beyond preventing habitat destruction resulting from anthropogenic activities by protecting species from exploitation within a defined area, MPAs are also expected to have beneficial effects outside the protected perimeter through the spill-over effect (i.e. net emigration of adult and juvenile fish) and export of pelagic eggs and larvae from restored spawning stocks within the MPA (Harmelin-Vivien et al. 2008; Stobart et al. 2009; Garcia et al. 2013). More than 100 MPAs have been established in the Mediterranean Sea since the 1960s (Abdulla et al. 2009). However, the most recent investigations suggest that Mediterranean MPAs do not perform as expected in several important respects. First, they do not meet international conservation goals (e.g. Aichi Target 11 of the Nagoya CBD Strategic Plan for Biodiversity, aiming at protecting at least 10% of coastal and marine areas by 2020) with less than 4.6% of the surface area of the Mediterranean continental shelf covered, i.e. 114 600 $km^2$ (1.1% if we exclude the Pelagos Sanctuary, which is dedicated to the protection of marine mammals) (http://www.medpan.org). Second, MPAs were established based on national or local initiatives and lack cross-regional consistency (Guidetti et al. 2008, Claudet & Guidetti 2010)). Finally, there is evidence for a mismatch between MPAs and the current state of Mediterranean marine biodiversity, with 70% of fish species failing to benefit from improved protection in the current MPA system than could be expected if MPAs were located at random across the continental shelf (Guilhaumon et al. 2015) and Mediterranean MPAs do not protect a substantial proportion of species at risk (Coll et al. 2015) and consensus areas for conservation (Micheli et al. 2013).

Since climate change affects marine species in a number of ways scaling from individual (e.g. vital rates, mortality, timing of migration) to populations (shifts in abundance-size structure or in spatio-temporal distribution), the potential beneficial effects of MPAs on marine populations facing climate change will depend on their ability to enhance the resistance of the populations to these different impacts and to adapt to changing spatial distributions of marine species.

Regarding individual fitness and population resilience, MPAs can act as enhancers and disrupt the detrimental synergistic effects between climate change and fisheries. By maintaining larger individual sizes and higher larval production and recruitment compared to fished populations outside reserves, MPAs enhance the resilience of exploited populations (Micheli et al. 2012).

Beyond the poor performance of the Mediterranean MPA system with regard to current biodiversity patterns, the efficiency of Mediterranean MPAs in the future is called into question by the impacts of climate change on marine populations. Indeed, conservation actions, such as the protection of land or sea, have traditionally been implemented under the assumption that species geographical distributions change relatively slowly, unless they are directly affected by human activities (Araújo 2009). However, climate change is predicted to have profound impacts on the geographical distribution of Mediterranean organisms over the 21st century. For example, modeling studies predict that 25% of the Mediterranean continental shelf will have undergone a complete modification of the endemic fish assemblages by the end of the 21st century (Ben Rais Lasram et al. 2010) (see sub-2.1.3). In a context in which marine species are shifting their geographical ranges, MPAs can lose the very same species that justified their implementation, therefore calling their future relevance for biodiversity conservation into question (Alagador et al. 2016). In the Mediterranean Sea, we observed a strong bias in the geographical distribution of MPAs, with a higher density of MPAs on the northern coast of the Mediterranean Sea than on the southern coast with only eight MPAs located on the North African continental shelf out of the 99 included in the study (Figure 4) (Guilhaumon et al. 2015).

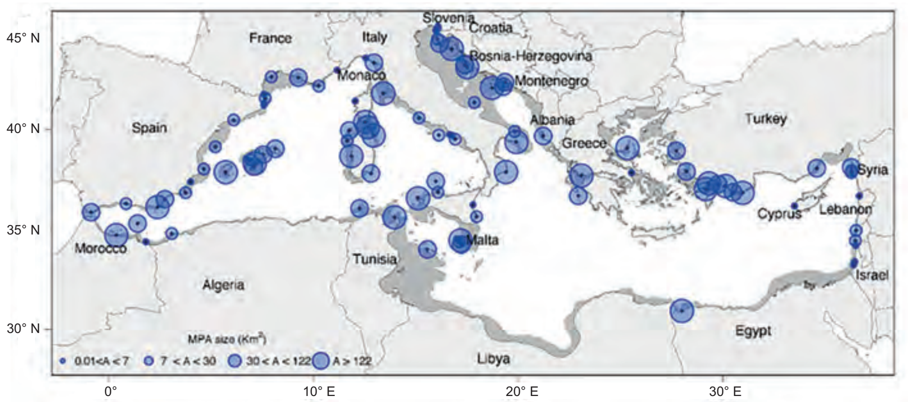


*Figure 4*
*Map of the Mediterranean Sea showing the continental shelf in grey and the location of the 99 MPAs mentioned in the study by Guilhaumon et al. (2015) (blue circles whose size is proportional to the size of the MPA).*

Although this geographical bias may be responsible for the current poor performance of the Mediterranean MPA system (Guilhaumon et al. 2015), it can also be seen as an opportunity for the future conservation of fish species. Since endemic and native fish are expected to move northward in the Mediterranean due to sea warming (Ben Rais Lasram et al. 2010; Albouy et al. 2012, Cheung et al. 2015), a potential increase is possible in the congruence between native and endemic biodiversity patterns and MPAs. However, the small size of MPAs on the northern Mediterranean coast and the lack of MPAs in the south are not only obstacles to rebuilding overexploited populations but may also prove problematic for the conservation of newly exploited tropical and subtropical species.

Future climate change may also have notable impacts on connectivity patterns between MPAs and other natural refuges of marine species (such as deep sea canyons and rocky areas). But although connectivity between MPAs is a critical criterion in the design of MPAs, it has not yet been taken into account when establishing MPAs in the Mediterranean Sea. In a recent publication based on the SRES IPCC A2 scenario, Andrello et al. (2015) explored the effects of adult reproductive timing and larval dispersal on the connectivity among MPAs and their ability to seed fished areas with larvae in the Mediterranean. These authors show that, over the 1970-2099 period, larval dispersal distances would decrease by 10%, the continental shelf area seeded with larvae will decrease by 3% and larval retention inside MPAs would increase by 5% (i.e. a higher concentration of larvae in smaller areas of the continental shelf). In fact, these results suggest that climate change will produce higher benefits for fished areas surrounding the MPAs but lower benefits for fished areas that are located too far from the MPAs (Andrello et al. 2015).

Climate change could influence the connectivity and the effectiveness of MPA networks via changes in hydrodynamics, adult reproductive timing, larval growth rates and shifts in population range. The fact that Mediterranean protected areas are geographically fixed, and increasingly isolated by habitat destruction, could be cost-ineffective, as major investments are being made today in areas that will potentially have limited positive impacts in the next several decades (McLeod et al. 2008). Thus, for scientists, managers and planners, designing adaptive and effective MPA networks in the face of climate change is a challenge.



## Current stock assessments in the context of climate change

The global climate change context questions the relevance of current models for managing ecological resources and fisheries stocks (Hoegh-Guldberg & Bruno 2010). Lack of understanding of the sources of temporal variability in fish abundance affects the robustness of biological reference points, decision making, and risk assessment in precautionary fisheries management (Hsieh et al. 2006). For instance, Brander (2010) wrote that: "*Reductions in stock productivity mean that levels of fishing to which a stock was previously resilient, become unsustainable. The decline will be exacerbated if underlying changes in growth are not recognised*". As mentioned above, climate change acts on several population processes including mortality, maturity, growth, distribution and recruitment that influence the levels of biomass produced. However, these processes are involved in the definition of biological reference points used as thresholds and targets in fisheries management strategies and decision making. Since the production of biomass is uncertain in the context of climate change and is subject to greater variability, these targets and biological reference points should be adapted to take these risks into account (Grafton 2010). Ignoring the effects of climate change in stock assessment could compromise the validity of stock forecasts and rebuilding plans (Brander 2010; Link et al. 2011). For example, ignoring the fact that fish may shift their range, and not including spatial dynamics could significantly affect the management advice based on stock assessment and associated projections (Link et al. 2011). It is crucial that the effects of changes in ocean properties (i.e. temperature, oxygen, carbonate system, etc.) are incorporated into stock assessment, and that their combined effects with fishing are quantified, in order to build ecosystem-based fisheries management.

According to the evaluation of the current state of the resources and the projected impacts of climate change, the future of the Mediterranean Sea appears to be jeopardized. The levels of exploitation of most assessed fish stocks are outside safe biological limits and several fish populations are now endangered by the strong impacts of this millennium activity (Tsikliras et al. 2015). In the context of global change, combined with other anthropogenic disturbances such as biological invasions, pollution, habitat losses and in particular, climate change, the biological and physicochemical features of the Mediterranean Sea are changing at an unprecedented rate. The lack of data and the poor knowledge of the status of existing stocks, especially in the southern and eastern parts of the Mediterranean, strong human population pressure along the coasts of the basin, and weak governance at regional scale threaten the conciliations of biodiversity conservation and sustainable fisheries management.

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Chapter 2

# Impacts on the coastal zone

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## Abstract

Sea level rise is a major challenge for the Mediterranean Sea, where risks related to coastal flooding and shoreline retreat are already a serious concern, and where many human, cultural, industrial and environmental assets are concentrated near the coastlines. The first part of the chapter shows that marked impacts on the coastal zone are to be expected. While adaption to more frequent high water levels during storms is recognized as inevitable, large generalized shoreline retreats can still be avoided if the sea level does not rise too quickly and global warming remains below 2 °C. The second part of the chapter investigates the influence of climate and non-climate drivers on coastal zones. Using a multi-scale coastal risk index including hazard, vulnerability and exposure, risk assessment of Mediterranean coastal zones revealed many hot-spots along the southern and eastern shores, whose adaptability is limited by weaker economic and institutional conditions as well as poor availability of financial and technological resources. The third part of the chapter presents a threatened icon of the Mediterranean coast: Lithophyllum byssoides, a calcified cushion-like red alga, which, as the result of the coalescence, stacking and persistence of

individuals, forms algal rims that are highly resistant to waves and storms. The bioconstruction of these rims is only possible under a stable or slightly rising sea level. Today, these algal rims have begun to be submerged. As the current rate of sea level rise appears to be accelerating, the rims would seem to be condemned.



# Résumé

L'élévation du niveau de la mer représente un défi majeur pour la mer Méditerranée, où les risques liés aux inondations et à la retraite du littoral sont déjà une préoccupation sérieuse, et où la population, des biens culturels, industriels et environnementaux sont concentrés près des côtes. La première partie du chapitre montre que de grands impacts sur la zone côtière sont attendus. Alors que l'adaptation à des hauts niveaux plus fréquents pendant les tempêtes est obligatoire, des retraites importantes et généralisées du littoral peuvent encore être évitées si le niveau de la mer ne monte pas trop rapidement et que le réchauffement climatique reste en dessous de 2 °C. La deuxième partie du chapitre examine le rôle des facteurs climatiques et non climatiques sur les zones côtières. L'utilisation d'un indice de risque côtier multi-échelle, qui intègre le risque, la vulnérabilité et l'exposition, pour évaluer les risques des zones côtières de la Méditerranée a fait ressortir de nombreux-points chauds sur les rives sud et est, là où la capacité d'adaptation est généralement limitée par de plus faibles conditions économiques et institutionnelles, ainsi que par la moindre disponibilité de ressources financières et technologiques pour les plus pauvres. La troisième partie du chapitre présente une icône menacée de la côte méditerranéenne: les byssoides *Lithophyllum*, une algue rouge qui forme des coussins calcifiés formant, par coalescence, empilement et persistance des individus, des trottoirs résistants aux vagues et aux tempêtes. La bioconstruction de ces trottoirs est seulement possible avec des niveaux de mer stables ou légèrement en hausse. Actuellement, ces trottoirs ont commencé à être submergés. Le taux actuel de l'élévation du niveau de la mer semble être trop rapide et les trottoirs semblent être condamnés à disparaître.

Sub-chapter 2.2.1

# Sea level rise and its impacts on the Mediterranean

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## Introduction

Since the late 19th century, global mean sea level has risen by 15 to 20 cm due to ocean warming and glacier melting caused by the anthropogenic climate change. While future sea level projections remain uncertain, the sea level will continue to rise during the 21st century and beyond. However, with unabated greenhouse gas emissions, the rate of about 3 mm/year observed during the last 20 years will probably accelerate and reach values comparable to the last marine transgression that took place from 21,000 to 6,000 years before present (B.P.). This is a major concern for the future of the majority of low lying coastal areas in the world, especially if extensive melting of the Greenland and Antarctica ice sheets leads to a rise of several meters in global sea levels over the coming centuries (IPCC, WG1, Ch13, 2013; Clark et al. 2016).

In this general context, the case of the Mediterranean Sea deserves special attention. First, exposure to coastal hazards is a real concern, as illustrated by historical events. Second, this region is particularly vulnerable to climate change:

comparisons with other coastal regions of the world have shown that Mediterranean cities, wetlands and dry lands are expected to undergo the most damage according to sea level rise projections for the 21st century.

Authors of current impact studies recognize that they are limited by the sparse knowledge regarding sea level changes in this semi-enclosed basin. Indeed, the Mediterranean Sea is not only connected to the global ocean through the Strait of Gibraltar, implying that sea level is controlled by local and remote processes, but it is also affected by vertical ground motions due to active tectonic and volcanic processes or caused by changing water volumes in subsurface sedimentary layers (e.g., due to groundwater extraction).

This raises the following questions: to what extent could the Mediterranean Sea differ from the global mean? What impacts are to be expected under plausible sea level change projections? Finally, what are the implications of these findings for adaptation and the mitigation of climate change? This article examines these three questions in turn.



## Sea level rise in the Mediterranean: why is it so complex?

### Present day sea level changes and the role of vertical ground motions

Sea level observations using satellite altimetry showed an increase in absolute (geocentric) sea level of 2.6±0.2 mm/yr on average across the Mediterranean Sea during the period 1993-2015 (Figure 1). Different features can be observed within the basin (Figure 1a), with linear trends ranging from -4 to 6 mm/yr, although these are associated with ocean circulation variability rather than long term and persistent structures. For the pre-altimetry period, i.e. prior to 1992, sea level observations are provided by tide gauges. The Mediterranean basin is monitored by a large number of tide gauges, and some records span several decades (see Figure 1b for some examples); however, with a very few exceptions, these gauges are concentrated along the European coasts. The longest tide gauge records in the Mediterranean Sea (Marseille, Genova and Trieste) report a rate of around 1.2±0.1 mm/yr in sea level rise in the 20th century. In contrast to satellite altimetry, tide gauges measure sea level changes relative to the land on which they are grounded. This means that the signal they measure includes vertical land motion in addition to the climate related signal from the ocean (Wöppelmann and Marcos, 2016). The most recent GPS solution (ULR6) produced by the University of La Rochelle Consortium, shows linear rates of vertical land motion varying between 1 and -4 mm/yr (fig. 1a). As in the case of the tide gauges, either continuous or episodic GPS observations are mostly made along the northern coasts of the Mediterranean Sea.

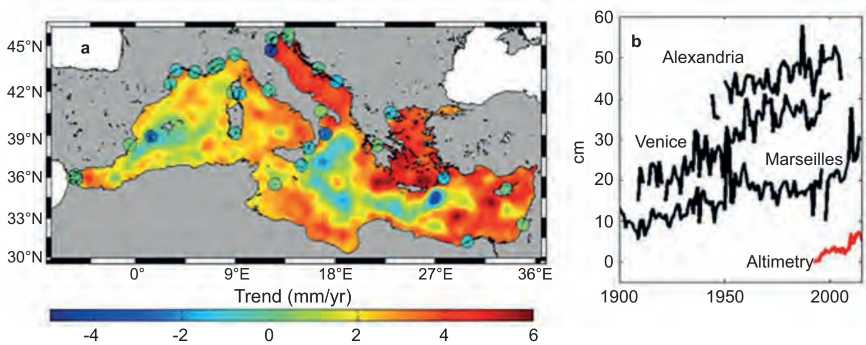


*Figure 1*
*a) Linear sea level trends for the period 1993-2015 computed from regional sea level anomalies provided by AVISO a reference portal in altimetry). Circles correspond to GPS vertical velocities from the ULR6 solution; b) yearly sea level time series from altimetry averaged over the Mediterranean Sea (red) and from three tide gauges.*

Rates of vertical land motion can be comparable in magnitude to climate related sea level changes (Wöppelmann and Marcos, 2016), thus mitigating (in the case of uplift) or exacerbating (in the case of subsidence) the impacts of sea level rise such as future flooding risks. A paradigmatic case is the city of Venice (Figure 1b) with a rate of 2.5 mm/yr in sea level rise in the 20th century, of which about 1.2 mm/yr is due to local subsidence. The city of Alexandria was also considered to be one of the most exposed to coastal flooding due its location on the Nile Delta (Hanson et al. 2011). However, it was subsequently demonstrated that Alexandria is only subject to moderate subsidence (Wöppelmann et al. 2013), implying very different evaluation of the future coastal risks. Therefore, accurate knowledge of rates of land motion is of paramount importance in the assessment of potential damage due to increased exposure to sea level rise.

## Future projections of mean sea level in the Mediterranean

The variability of the Mediterranean Sea level is caused by different mechanisms. Local processes such as changes in the circulation, in the local thermal expansion or in the atmospheric mechanical forcing are combined with remote processes represented as the changes in the northeast (NE) Atlantic sea level. The answer to the question of which mechanism dominates depends on the time scales considered. While atmospheric mechanical forcing dominates at intraseasonal scales (Jordà et al., 2012a), at multidecadal timescales, variations in sea level in the northeast Atlantic are the dominant mechanism. Therefore, in order to obtain reliable projections of Mediterranean Sea level, the numerical models need to consider both local and remote forcings. Realistic simulation of the level of the Mediterranean Sea can be obtained by decomposing the signal into two components: relative variations in the Mediterranean Sea level with respect to the nearby NE Atlantic, and variations in the NE Atlantic sea level. This is an important consideration given that most regional climate models of the Mediterranean Sea do not include variations in the Atlantic sea level in their configurations, while the coarse resolution of global models prevents them from correctly reproducing processes that take place within the basin. For these reasons, here we generate the projections of Mediterranean Sea level combining the results of global climate models (GCMs) for the variations in the NE Atlantic and the results of regional climate models (RCMs) for the relative changes between the sea level of the Mediterranean Sea and of the NE Atlantic.

The projections of NE Atlantic sea level were obtained using the CMIP3 and CMIP5 simulations for the moderate scenarios SRES-A1b and RCP6.0 and the high emission scenarios SRES-A2 and RCP8.5. The GCM simulations take into account projected changes in thermal expansion and in the circulation but not the contribution of terrestrial ice melt. For the latter component, we used the results of Spada et al. (2012) who solved the sea level equation to investigate the pattern of the gravitationally self-consistent sea level variations corresponding to future scenarios of terrestrial ice melt. Finally, the projected changes in the relative differences between Mediterranean Sea level and NE Atlantic sea level were obtained from an ensemble of regional models. In particular, we used RCMs to simulate the changes related to circulation and local thermal expansion and storm surge models to simulate the changes related to atmospheric mechanical forcing.

The projections of changes in the NE Atlantic sea level caused by thermal expansion and changes in the circulation (fig. 2a) show an increase that ranges from 16 cm to 57 cm depending on the scenario. The projected mean values are 24, 32, 22 and 41 cm in the SRES-A1b, RCP6.0, SRES-A2 and RCP8.5 scenarios, respectively. These projected changes are a combination of the global thermal expansion (from 10 to 30 cm) with projected changes in the circulation (from - 3 to + 37 cm). The latter refers to the projected regional redistribution of water due to changes in the distribution of wind and water masses. It is interesting to note that the latter factor is expected to contribute significantly to the sea level in the NE Atlantic and hence to future changes in the Mediterranean Sea level. If we consider the relative differences between the Mediterranean and the NE Atlantic, we find that all the models show small changes, irrespective of the scenario concerned. The expected evolution in local thermal expansion and circulation only implies a small decrease ranging from - 3 to 0 cm with respect to the NE Atlantic. The atmospheric mechanical forcing would also have only a small impact (between - 2 and 2 cm with respect to the NE Atlantic). Finally, we can estimate the evolution of Mediterranean Sea level taking into account all the above mentioned factors as well as the terrestrial ice melt (fig. 2c). The results show that the basin average Mediterranean Sea level will increase by between 44 cm and 102 cm by the end of the 21st century. The mean values are 60, 68, 57 and 76 cm in the SRES-A1b, RCP6.0, SRES-A2 and RCP8.5 scenarios, respectively. In sum, the Mediterranean will basically mirror the evolution of the NE Atlantic, which, in turn, is expected to reach higher levels than the global mean sea level because of the expected changes in the circulation.

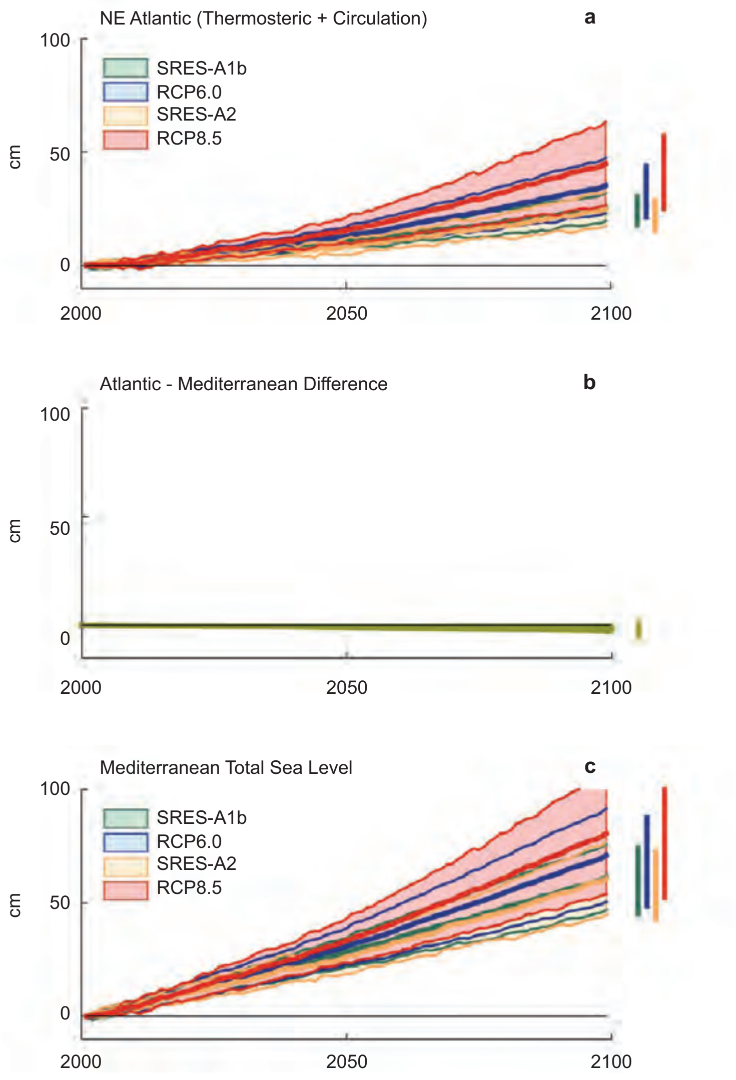


*Figure 2.*
*Projections of the basin averaged Mediterranean sea level in different scenarios and for different components.*
*(a) Changes in the Northeast Atlantic sea level caused by circulation and thermal expansion.*
*(b) Difference between the sea level in the Mediterranean and in the northeast Atlantic. Note that we include all the available simulations but without distinguishing between scenarios (see text for details).*
*(c) Mediterranean total sea level, which is the combination of (a)+(b)+contribution of terrestrial ice melting.*

It is worth noting that these projections refer to the basin average sea level. The regional models show a complex pattern of changes within the Mediterranean including local changes that can differ by + 10 cm from the above mentioned values. However, the results of the different RCMs are not consistent and the ensemble is too small to draw robust conclusions. Therefore, we recommend taking into account that, at local scale, the projected values can differ by up to + 10 cm with respect to the basin average values.



## Impacts of sea level rise on shorelines and on coastal flooding in the Mediterranean

During storms, several physical phenomena cause to water to rise above the predicted levels. In addition to the effects of direct atmospheric forcing (lower pressure and strong winds), the increase in mean water level may be due to the presence of breaking waves, called the wave setup. If the sea level at the coast exceeds the height of coastal defenses or dunes, the result is coastal flooding generated by overflow. Otherwise, the instantaneous effect of each individual wave can still cause overtopping and flooding.

With the projected increase in sea levels, extreme surge events associated with atmospheric storminess become potentially more hazardous threats to the coastal environment. Although the intensity and frequency of extreme sea levels vary independently of mean sea level, these changes are small compared with rates of mean sea level change. Assessment of projected changes in storm surges in the Mediterranean Sea has revealed that expected variations are towards less frequent/more intense extreme events, possibly associated with a northward shift of the Atlantic storm tracks. However, the projected changes in storminess are relatively modest and would not compensate for the expected increase in the mean sea level.

Box 1 illustrates all these phenomena with historical storms in Languedoc Roussillon (region on the French Mediterranean coast). For example, in situ and modeling data show that during the 1997 storm, atmospheric forcing caused a sea level rise of 0.4 m with an additional 0.4 m caused by the wave setup in the harbor of Sète. In such cases, the values reached by the wave setup are far from negligible, and depend to a great extent on the slopes of the subseafloor in shallow waters. Hence, extreme water levels will differ from site to site, depending on the local topography, bathymetry and defense systems built. This illustrates the need to take the local context and how it changes over time into account for accurate coastal impact assessments.

Despite the need to consider the local context, a general conclusion has been drawn from all the studies that examined future coastal flooding under the assumption that

### Box 1
### Impacts of sea level rise in the case of coastal flooding in Palavas les Flots, France

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Over the past decades, Palavas les Flots (Gulf of Lion, France) has been affected by several marine flooding events, notably in 1997 and 1982. In the framework of the ANR-funded MISEEVA project, the impacts of similar events were investigated using several sea level rise projections. The figure below shows that for an event similar to the 1982 flood, much larger water depths and flow velocities are to be expected with a sea level rise of only 0.35 m (sub-figure B), while with a one meter sea level rise, the entire sand spit would be flooded (sub Figure C). These simulations are based on the implementation and validation of nested models, ranging from the modeling of waves and water levels in the western Mediterranean, while explicitly taking into account the built-up environment and the coastal protection structures (Pedreros ***et al.,*** 2011). It illustrates both the maturity of such models and the need for adaptation to a 35 cm rise in sea level, which is the low end scenario for the 21st century.

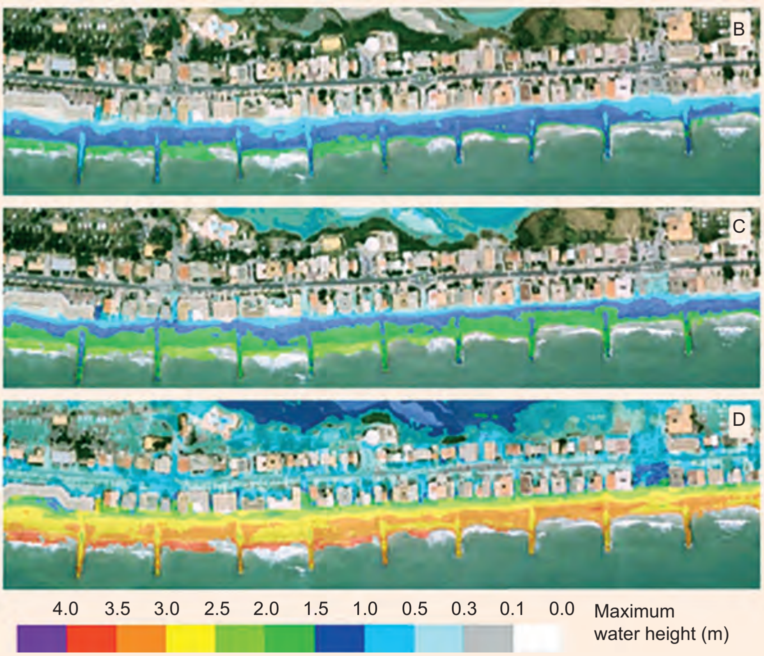


*Figure B.1*
***Modeling of coastal flooding in Palavas Les Flots. Maximum height of the water in the flooded area during the historical event (B), for the historical event plus a sea level rise scenario of 0.35 m (C) and a rise of 1 m (D). In the latter case in D, the entire sand spit is flooded.***
***Source: Pedreros et al. 2011.***

*Box based on an article published in Géosciences, 2015 - Géosciences, (spécial» Géosciences et Changements climatiques»), pp-16.*

sea level follows global or regional IPCC projections (Hallegatte et al. 2013): without adaptation, coastal flooding will not only become more intense (as shown in Box 1), but also more frequent, especially in the Mediterranean region. The latter issue is illustrated in Figure 3 using data from Hallegatte et al. (2013) in the case of Alexandria (Egypt), assuming that the sea level follows IPCC projections, and that vertical ground motions contribute less to relative sea level changes.

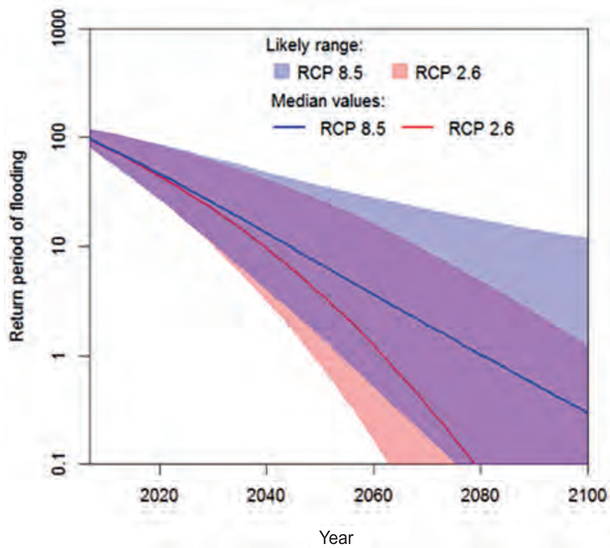


*Figure 3*
*Expected changes in the return period of flooding in Alexandria (Egypt). These results are based on the projections described in part 1 (Figure 2) and the IPCC global projections for RCP 8.5 and 2.6, respectively. Both curves take into account an additional +/-10 cm uncertainty due to intra-Mediterranean sea level variability. The curves use the data of Hallegatte et al. (2013), assuming negligible vertical ground motions (Wöppelmann et al. 2013). Note the logarithmic scale on the y-axis.*

The expected increase in the frequency and intensity of storm surges has raised concerns regarding the possible increase in damage in the future. In large cities, both risks and adaptation capabilities are large, so investments needed to ensure the same level of protection are indispensable (Hallegatte et al. 2013; Hunter et al. 2013). However, the Mediterranean coasts are also characterized by many rural, peri-urban and tourist resorts and small harbors, where funding and local knowledge might not be sufficient to address the issue of coastal adaptation.

## Shoreline retreat

Coastal erosion already affects a large part of the Mediterranean shores. The coastal database Eurosion (www.eurosion.org) contains information on changes in the shorelines of European member states collected from 1980 to 2000. Along the Mediterranean and Black Sea coasts, this dataset shows that for the 6,750 km

Box 2
## Integrated quantitative assessment of the impact of climate change on Mediterranean coastal water resources and socio-economic vulnerability mapping: The MEDAQCLIM project

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The Mediterranean region is very sensitive to climate change extremes. These coastal environments share common water management problems due to their overexploitation, pollution of fresh water, sea level rise, seawater intrusion and land losses. The increased complexity of policy making in these sites is an ongoing challenge to managers. The objective of the ERANET-MED MEDAQCLIM project (2016-2019) is to identify the impacts of climate change on water resources in coastal zones, the resulting socio-economic vulnerability and the need for sustainable development. An integrated quantitative assessment will achieve this goal by combining projections from climate change scenarios with advanced computational hydrological impact assessment models to identify vulnerability hot-spots. Particular emphasis will be on optimal water resources management in six selected coastal sites in France, Morocco, Algeria, Tunisia and Greece. The project will design simulation scenarios addressing climate change uncertainty to improve water resources management practices and to inform decision makers on the best adaptive measures depending on future climate trends. Screening numerical simulations are shown in Fig. B.2 to illustrate the relative contributions of different sources of projected anthropogenic forcing such as aquifer recharge, sea level rise and groundwater abstraction on saltwater intrusion and degradation of groundwater quality. In this case, the landward advancement of the interface toe due to 1.5 m sea level rise alone exceeds 400 m. The problem becomes more alarming due to groundwater abstractions leading to enhanced vertical displacement of salt water or the so-called well upconing phenomenon.

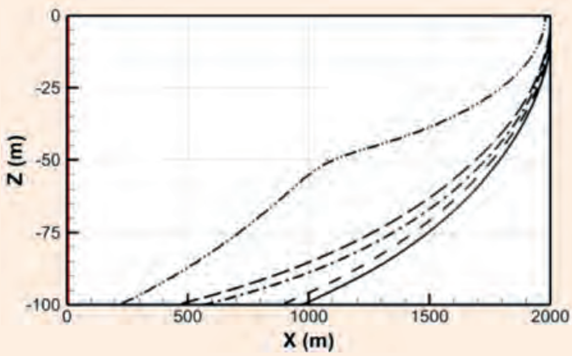


*Figure B.2*
*Numerically simulated landward advancement of the salt water interface in a hypothetical head controlled, 110 m thick (top 10 m not shown here), unconfined aquifer. The steady-state interface positions shown are simulated under (i) natural conditions (solid line), (ii) with a 50% decrease in aquifer recharge (dashed line), (iii) with a 1.5 m sea level rise (dashed dotted line), and (iv) with the combined impacts of a decrease in recharge and sea level rise (long dashed line). The last interface position (dash double dots) represents the salt water upconing phenomenon, which results from the additional contribution of groundwater abstraction by a shallow well screened at X=1,000 m and at a depth of between 5 and 10 m.*

of sandy beaches for which information exists, 3,400 km were already eroding during that period, while only 580 km were accreting. This raises significant management issues not only on the northern shore of the Mediterranean, but also on the southern shores, as shown by the growing number of studies addressing the issue of shoreline retreat (see section 2.2.2).

While it is widely acknowledged that future sea level rise will exacerbate coastal erosion, current assessments of future shoreline changes suffer from large uncertainties. Obviously, a rapid extensive sea level rise (typically 2 to 4 m/century) would result in the permanent flooding of the lowest coastal areas. However, as long as sea level continues to rise a few millimeters a year, a dynamic response of the shoreline is to be expected. Figure 4 shows evaluations of future shoreline change rates for typical Mediterranean beaches in the Gulf of Lion, France, which are currently severely affected by erosion.. These simulations provide very different perspectives depending on future greenhouse gas emissions: on the one hand with reduced greenhouse gas emissions (RCP 2.6), shoreline change rates would be little affected by sea-level rise; on the other hand, unabated emissions would result in a significant acceleration of shoreline retreat. These results are based on assumptions that are debated in the scientific literature. However, they support the fact that an acceleration of sea-level rise could result in notable losses of beaches and coastal wetlands on both southern and northern Mediterranean shores.

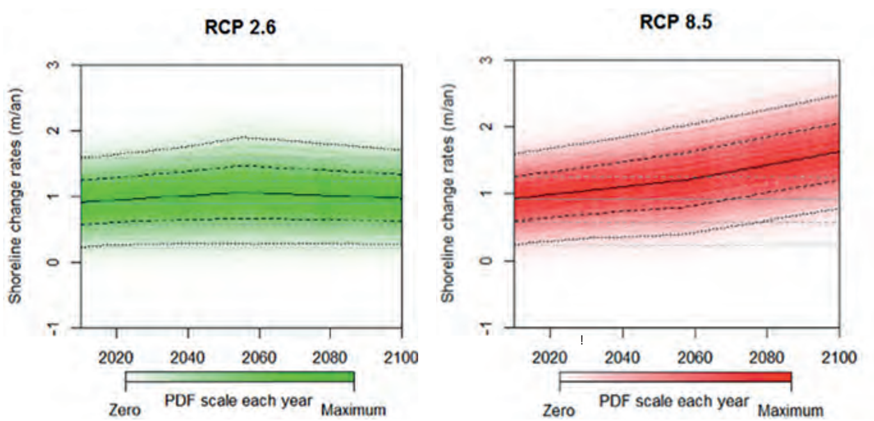


*Figure 4*
*Probabilistic shoreline retreat projections*
*for the northern Mediterranean in Languedoc (France) as a function of time (2010 to 2100).*



# Conclusion

While adaptation to current environmental conditions is being increasingly addressed in current risk prevention policies, the possible impacts of future sea level rise are the subject of fewer studies. It is however certain that, particularly in the Mediterranean region, future adaptation will be especially difficult if sea level rise reaches or exceeds rates of 1 cm/year, as predicted by GHG emission scenarios. Therefore, public policies addressing the future challenges of Mediterranean coastal hazards should not only focus on adaptation, but also mitigate climate change by reducing concentrations of GHG in the atmosphere.

## Acknowledgements

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# Vulnerability of the Mediterranean coastal zones faced with the risk of climate change

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## Introduction

Coastal communities and assets have been repeatedly threatened by the unpredictable sea conditions. Scientific evidence suggests that more intense storm surges and accelerated sea-level rise, related to climate change, are serious global threats for coastal areas and human society (IPCC, 2012). In the Mediterranean region, where nearly 40% of the coastline is built up and given the effects of future human encroachment on the coast, local authorities are faced with the increasingly complex task of balancing development and managing coastal risks, especially coastal erosion and flooding. Investigating the role of climate and non-climate drivers on coastal zones is therefore crucial to understand the underlying risks and identify appropriate and cost efficient response measures.

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014), the risk of climate related impacts results from the interaction of climate related hazards with the vulnerability and exposure of human and natural systems, and changes in both the climate system and socio-economic processes are the key drivers of vulnerability, exposure and hazards. In this context, a comprehensive approach, based on a multi-risk method (Torresan et al. 2012; Satta et al. 2015; Gallina et al. 2016), is the most valuable tool that can be directly applied in coastal development programs in both the short and long term, and can assist decision makers in the implementation of preventive management strategies in the most sensitive areas. However, assessing current and future vulnerabilities and risks to coastal hazards is a challenge for both researchers and policy makers. It is important to understand that the assessments remain inherently uncertain, as they are derived from a process necessarily involving assumptions about a number of key factors, based on best available projections and expert knowledge (Markandya et al. 2016).

## Multi-scale coastal risk assessment for the Mediterranean

Satta et al. (2015) developed and applied a multi-scale coastal risk index, whose application at the regional scale (the Mediterranean basin) was called CRI-MED. This index has several advantages that make it particularly suitable to support decision making despite scarce resources, limited local data (especially along some of the southern and eastern shores of the Mediterranean) and uncertain information about the future. The CRI-MED is composed of three sub-indexes:

1. Coastal forcing, characterizing the variables related to climate hazards (storms, drought, sea-level rise) and non-climate forcing (population growth, the number of tourists);

2. Coastal vulnerability, integrating the resilience variables (age of the population, level of education) and coastal vulnerability variables (landform, elevation);

3. Coastal exposure, describing coastal locations potentially at risk, the exposure (land cover, population density).

The selected variables contribute in different ways to the risks affecting Mediterranean coastal zones and must be weighted accordingly for accurate calculation of CRI-MED. For the purposes of this study, sea level rise, storminess, as well as landform and elevation of coasts are considered to play the most significant roles in generating coastal risk.

The CRI-MED spatial index combines multiple variable layers, representing different aspects of risk, in sub-indexes (vulnerability, forcing and exposure) layers, in such a way that risk hot-spots as well as areas of relatively lower risk emerge from the integration of the layers (Satta et al. 2015). The values for each variable, represented by a layer, are normalized to a consistent ordinal or unitless scale. The scaled layers are then averaged or summed to come up with a score referring to its contribution to coastal risk. The application of the CRI-MED to 11 Mediterranean countries selected for the ClimVar project led to ranking of the relative risk of each coastal region in relation to potential coastal hazards (coastal erosion, coastal flooding and saltwater intrusion) generated and/or exacerbated by climate forcing combined with human-induced forcing. The resulting risk map (Figure 1) represents the visualization and prioritization of risk in the coastal zones of the countries involved in the study. The final risk rankings are dimensionless numbers that judge the relative degree of risk of coastal zones to each coastal hazard analyzed, related to qualitative risk classes (i.e. extremely high, high, medium, low, extremely low). In this sense, higher risk values do not imply high risk in absolute terms, but only compared to other case coastal zones.

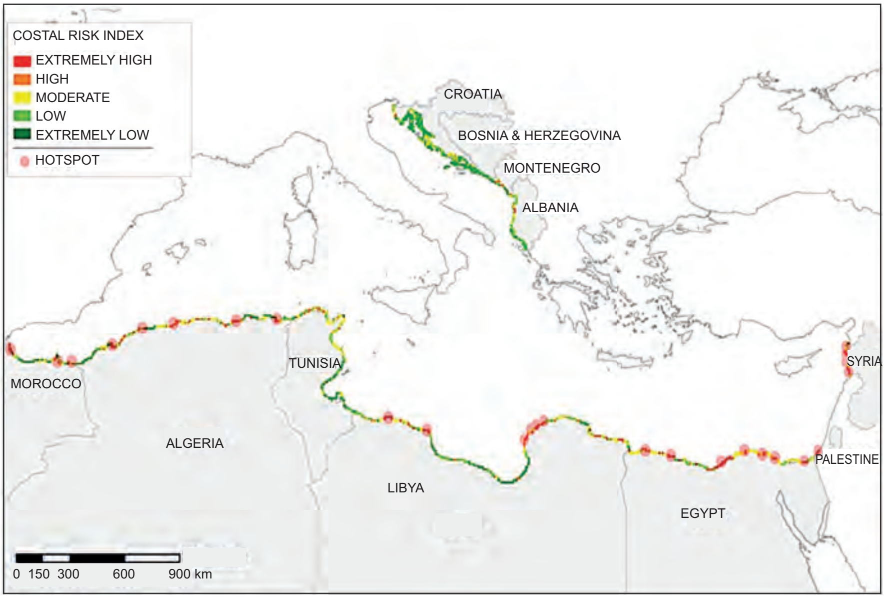


*Figure 1*
*Coastal risk map of 11 Mediterranean countries (Satta et al., 2015).*

The CRI-MED therefore makes it possible to list the coastal hot-spots identified in each country. Coastal areas at extremely high risk are mainly located in the southern Mediterranean region; the countries concerned by coastal hot-spots include Morocco, Algeria, Libya, Egypt, Palestine, and Syria. Other countries in the region have areas at high risk (colored orange on the map), for instance in Albania and other Adriatic coastal sites. Finally, as per methodological assumptions, the hot-spot threshold was set in a way to highlight only areas that appear exceptionally at risk according to the statistical distribution of cells, where areas at high risk are located next to areas that are also at high risk.

# Multi-scale coastal risk at the local scale (CRI-LS): the case of Tetouan coastline (Morocco)



The local spatial scale application of the multi-scale coastal risk index methodology is called CRI-LS and it differs in some respects from CRI-MED. The main differences concern the need to define the coastal hazard zone at the local scale. The coastal hazard zone is the zone affected by the occurrence of the hazard, which may cause damage to, or loss of, natural ecosystems, buildings, and infrastructure. Concerning this point, Article 8 of the ICZM protocol specifically provides the definition of setback areas for the Mediterranean coastal regions, considered as the landward limit of the buffer zone behind the coastline, beyond which the acceptable level of risk produced by coastal hazard is defined (Satta et al. 2015). As the main hazards that act as forcing in the Mediterranean region are erosion and flooding (Satta et al., 2016), the overall hazard zone results from the overlaying of the erosion hazard zone and the flooding hazard zone. Higher resolution is required at the local than at the regional scale. In fact, in order to obtain more detailed information to plan appropriate strategies, several more variables are introduced for the three sub-indexes of vulnerability and exposure at the local scale.

The first phase of the CRI-LS method consists in defining the coastal hazard zone, which results from the overlaying of the erosion hazard zone and the flooding hazard zone. Nineteen variables are proposed to describe the hazard, vulnerability and exposure sub-indexes (Table 1). The scores corresponding to

*Table 1*
*CRI-LS variables*

| **Coastal hazard sub-index** | **Coastal vulnerability sub-index** | **Coastal exposure sub-index** |
|---|---|---|
| Sea level rise | Landform | Land cover |
| Storms | Coastal slope | Population density |
| Mean annual max daily precipitation | Land roughness | |
| Drought events | Historical shoreline change | |
| Population growth | Elevation | |
| N° of tourists | Distance from the shoreline | |
| | River flow regulation | |
| | Ecosystem health | |
| | Education level | |
| | Age of population | |
| | Coastal protection structures | |

each variable are calculated and the weights assigned using expert knowledge. The resulting values are hosted on a geographic information system (GIS) platform that enables the individual variables and aggregated risk scores to be color coded and mapped across the coastal hazard zone.

Tetouan is one of the coastal areas identified as a hot-spot in the CRI-MED assessment (Satta et al. 2015). Indeed, the coastline has been evolving in a sediment-deficit context (due to damming of rivers and overexploitation of sand dunes) for the last two decades. In addition, it has been subjected to increasing

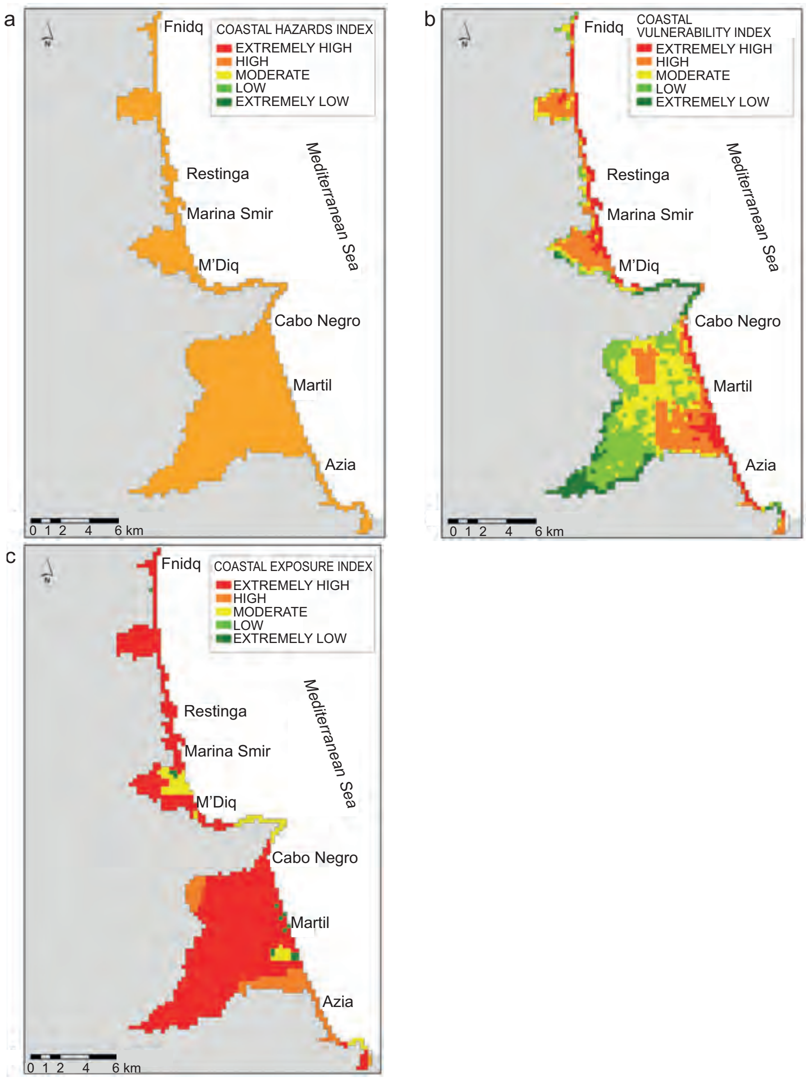


**Figure 2**
*Coastal forcing (a), Coastal vulnerability (b), Coastal exposure (c).*

human pressure, including the construction of residential buildings on the foredunes and on vulnerable low lying coasts, construction of leisure ports (M'diq, Smir Marina and Kabila) and a road network along the coast. Over 95% of the coastal dunes have been destroyed by housing and tourism infrastructure. These coastal developments have seriously disturbed cross shore sediment transport and/or interrupted sediment transport along the shore, leading to a severe coastal erosion. Like for the definition of the coastal erosion and flooding, the worst SLR and extreme wave conditions (100 year return period) scenarios to 2100 were used. The application of the CRI-LS to the coastal hazard defined for Tetouan led to the ranking of the values of forcing, vulnerability and exposure illustrated in figure 2.

Figure 2b shows that respectively 10% and 27% of coastline investigated are classified as very highly and highly vulnerable because of the combination of high erosion rates with high capital land use. The risk scores were obtained by multiplying the scores obtained by three sub-indices. In contrast to the CRI-MED index, here, higher risk values imply high risk in absolute terms and the proposed CRI-LS method makes it possible to rank the risk at the local scale of the study area. The risk map (figure 3) identifies areas within the coastal hazard zone with a relatively higher risk of climate related hazards. The risk map shows that some areas, especially the coastal plains, at distances of more than 5 km from the coast, are characterized by high levels of risk due to the low topography of the flood plains and to the high exposure values.

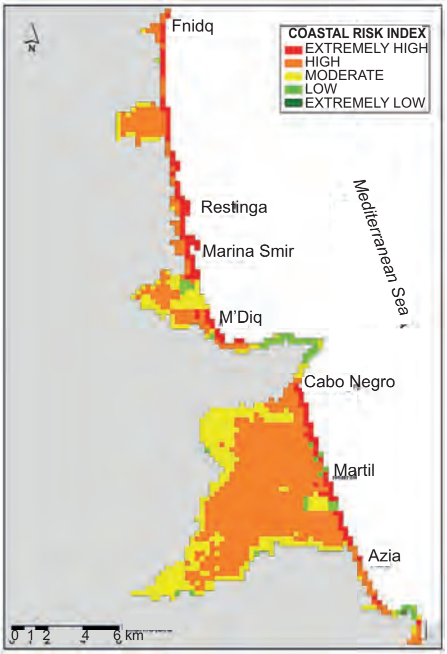


**Figure 3**
*Coastal risk index.*

For direct application in policies, the CRI-LS provides the definition of the coastal hazard zone under the 2100 scenario, and a set of risk maps to assist policy makers in prioritizing coastal management efforts that need to be undertaken to minimize risks or mitigate the consequences of climate and non-climate related hazards. This tool can be easily incorporated in overall coastal management and adaptation strategies to support the implementation of the integrated coastal zone management (ICZM) Protocol.

# Conclusion

Multi scale risk assessment of Mediterranean coastal zones revealed many hot-spots along the southern and eastern shores, mainly associated with urban low-lying centers that are under multiples pressures from land use patterns and practices. In both the short and medium term, Mediterranean Sea coasts will probably experience greater stresses produced by non-climatic factors such as population growth, intensification of tourism, poor land and water management, resource overexploitation, urbanization, and the development of coastal infrastructure. Climate change and related impacts are expected to be more severe in the southern and eastern parts of the Mediterranean basin, the adaptability of which is generally limited by weaker economic and institutional conditions as well as by poorer availability of financial and technological resources. A feature of the Mediterranean is the commitment of the multilateral community and its institutional structures to resolve problems by taking action, including regulation and legal instruments, policy and planning initiatives, capacity building and public participation mechanisms.

From the methodological point of view, the clear advantage of the multi-scale index is the choice of the balance between an overview and a detailed view. Users can chose the trade-off that is appropriate to their needs by selecting the most suitable index scale for the desired scale of management. The application of the MS-CRI at two different scales (CRI-MED and CRI-LS) emphasized that spatial scale is also an important aspect to take into account in the development of coastal vulnerability indices. No single scale is suitable for all needs. Different scales tend to reflect different priorities, and the influence of a given variable will increase or decrease as the scale changes (Satta et al. 2015). Multi-scale indices, like those presented here, can be used to assist coastal policy makers at different scales and scopes of application. Nevertheless, major differences exist between the regional and the local level (Satta et al. 2015). With CRI-MED, detail is sacrificed in order to gain an overview of the risk faced by the whole Mediterranean coastline, whereas, with CRI-LS, the level of detail is high but there is no real overview. It is up to the coastal manager or policy maker to determine the most appropriate scale or scales of index to apply, depending on whether the policy is national, regional or local. In an ideal world, indices would be based on local-level information that is aggregated and simplified as larger scales are considered. However, in terms of data availability, storage and processing, this is rarely feasible, given the time needed to undertake such risk assessment. Possible further developments could include creating an initial database of relevant methods and tools for risk and vulnerability assessment in the Mediterranean.

## Acknowledgements

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# The sea level rise and the collapse of a Mediterranean ecosystem, the *Lithophyllum byssoides* algal rim

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The Mediterranean is a hot-spot of marine and terrestrial epsilon species diversity (Boudouresque, 2004; Blondel and Médail, 2009; Coll et al. 2010). The Mediterranean Sea also harbors a wide range of ecosystems, some of whose structure and functioning are unique in the world. These ecosystems include midlittoral *Lithophyllum byssoides* rims, shallow vermetid platforms, the *Posidonia oceanica* seagrass meadow, the *Cystoseira* seaweed forest and the coralligene (e.g. Pérès and Picard, 1964; Laborel, 1987; Hereu Fina, 2004; Ballesteros, 2006; Boudouresque *et al.,* 2014; Personnic *et al.,* 2014) .

*Lithophyllum byssoides* is a calcified cushion-like red alga (Rhodobionta, kingdom Archaeplastida), which, as the result of coalescence, stacking, and persistence of the individuals, results in formations that are as hard as stone, and are highly resistant to waves and storms. In ancient publications, the species was known as *Tenarea tortuosa, Lithophyllum tortuosum* and *L. lichenoides*, which are not legitimate names. *Lithophyllum byssoides* thrives in rocky and shady habitats, in semi-exposed and exposed conditions, just above the mean sea level, in a zone characterized by the oscillation of the waves and tide, the lower mid-littoral zone (Fig. 1; Pérès and Picard, 1964; Laborel, 1987; Laborel et al. 1994; Boudouresque, 2004). *L. byssoides* bioconstructions are known as algal rims or '*trottoirs* and can reach a width of 2 m (Fig. 1; Bianconi et al. 1987; Laborel, 1987). *L. byssoides* is the autogenic ecosystem engineer of a unique ecosystem characteristic of the Mediterranean Sea. Although it belongs to the marine realm, this ecosystem forms a frontier between the marine and terrestrial realms: it harbors both typically marine taxa, such as the encrusting coralline red alga *Neogoniolithon brassica-florida* and typically terrestrial taxa such as the arachnid *Mizaga racovitzai* (Pérès and Picard, 1964).

*Figure 1*
*The Cala Litizia* Lithophyllum byssoides *rim*
*in Scàndula Natural Reserve, Corsica, in 1983. Its width can reach 2 m.*
*© J.-G. Harmelin (courtesy of the author).*

The bioconstruction of *L. byssoides* algal rims is only possible when the sea level is stable or a slightly rising (Laborel, 1987; Faivre et al. 2013). After the Last Glacial Maximum (LGM), ~20 ka ago), when the sea level was 120-130 m below the current sea level (Lambeck and Bard, 2000), the sea level rose steadily at a speed of up to 3.7 m/century (Collina-Girard, 2003). The current algal rims correspond to the LIA (Little Ice Age; $13^{th}$ through $19^{th}$ centuries CE), when the polar ice sheets stopped melting and Alpine glaciers advanced, more or less stabilizing the sea level. Former algal rims, which today are submerged and increasingly bioeroded by sea urchins (*Paracentrotus lividus*), date mussels (*Lithophaga lithophaga*), boring sponges (e.g. *Cliona* sp.) and Cyanobacteria, were constructed during the DACP (Dark Age Cold Period, ca. 2nd through 8th centuries CE) and in earlier cold periods (Fig. 2).

By the end of the LIA (mid-19th century), the sea level had resumed its rise. The rise was at first slow (0.4 mm/a) but, due to the human-induced amplification of climate warming, the sea level rise subsequently accelerated. It has now reached 3.4 mm/year (Nicholls and Cazenave, 2010). By the end of the 21st century, the rise will probably be within the range 26-82 cm, but a much greater rise in sea level cannot be ruled out. This rise should continue since at the end of three out of the last four interglacial periods, the maximum sea level was probably several meters above the current sea level (Waelbroeck et al. 2002).

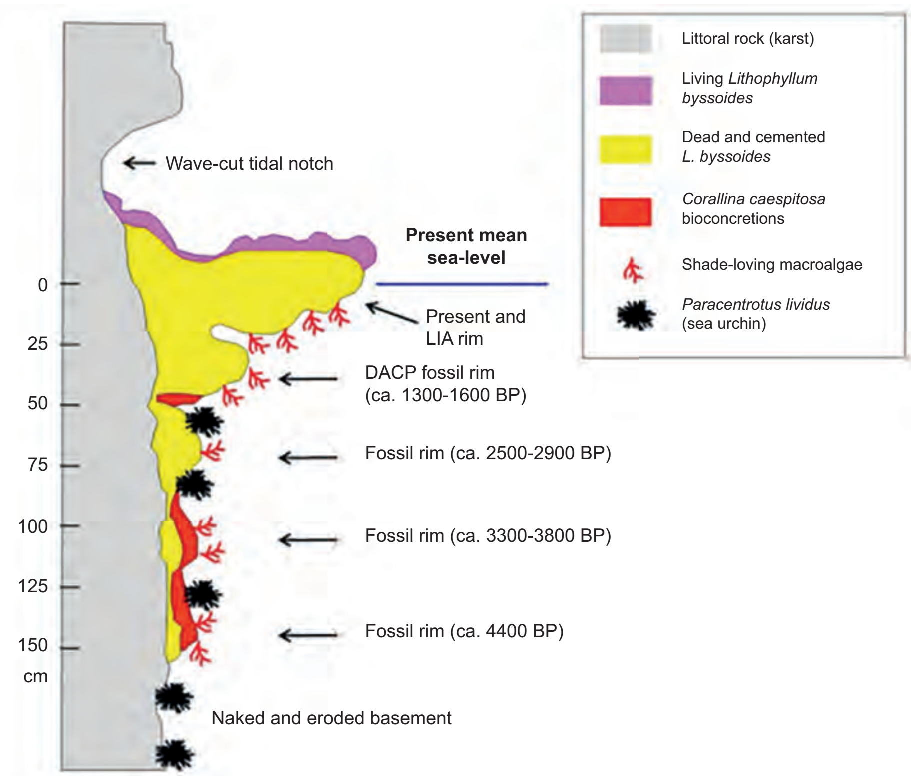


*Figure 2*
*Profile of a limestone cliff at La Ciotat (near Marseilles, Provence, France), showing the structure of the present* Lithophyllum byssoides *rim (LIA and post-LIA) and the remains of the previous submersed rims that are gradually disappearing under the influence of sublittoral bioerosion. From Laborel and Laborel-Deguen (1994, 1996), redrawn and simplified.*

*L. byssoides* algal rims have begun to be submersed throughout the Mediterranean Sea. While they formerly belonged to the lower mid-littoral zone, they have progressively 'shifted' to the infra-littoral zone (in fact, it is the infra-littoral zone that has 'shifted' upwards). The calcareous red alga *L. byssoides* then dies and is subsequently covered by infra-littoral species, such as soft red algae and articulated corallines (e.g. *Corallina caespitosa*). Simultaneously, the dead, 'fossil' algal rim is bioeroded by endolithic photosynthetic and non-photosynthetic borers and by grazers. The rim is perforated by holes of increasing size (Fig. 3), and its width and thickness decrease. Its total destruction may require five millennia. Under exposed conditions, the algal rim is protrudes higher above the mean sea level than under semi-exposed conditions; consequently, *L. byssoides* algal rims that thrive under semi-exposed conditions are more sensitive to the ongoing sea level rise (unpublished data).

Popular media and scientists often rightly draw the attention of the public to the flooding of Pacific atolls and the states that are affected as a result. Here, we draw attention to the fate of the Mediterranean algal rims and to the first forecast collapse of a marine ecosystem as the indirect result of global warming, through the sea level rise: the current rate of sea level rise appears to be too fast and *L. byssoides* rims thus appear to be condemned (Faivre et al. 2013; Thibaut et al. 2013).

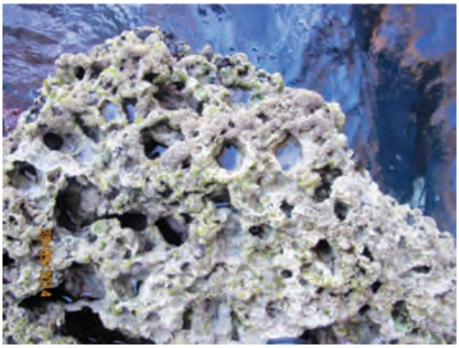

*Figure 3*
*A dead, highly bioeroded,* Lithophyllum byssoides *rim,*
*at Punta Palazzu (Natural Reserve of Scàndula, western Corsica).*
*© T. Thibaut.*



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Chapter 3

# Impacts on water and soils

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## Abstract

This chapter presents research outputs concerning the expected relative impacts of anthropogenic and climate changes on water and soil resources in the Mediterranean region, and their associated vulnerabilities. First, in subchapter 2.3.1., the current methods and their limits are outlined. The main projected changes due to the rise in temperature concern evapotranspiration (increased climatic demand, more water limiting cases) and snowfall (less snow, melting occurs sooner), as well as the possible increased intensity and frequency of extreme events (droughts and floods, subchapter 2.3.2). Rainfed agriculture is particularly threatened. The expected impacts of changes in precipitation patterns and land use on soil erosion are assessed in subchapter 2.3.3. The challenge of foreseeing the impacts of extreme rainfall events on floods is documented in subchapter 2.3.4. The difficulty involved in maintaining long term monitoring of those resources, with little funding available to support a dense gauging network, encourages us to develop alternative observation systems based on distributed data acquired through remote sensing (2.3.2) or post-event inquiries (2.3.4), for example. Current human activities may occasionally reduce certain vulnerabilities

(for example through soil and water conservation systems) but more often exacerbate the negative impacts of climate change on soil and water resources; for example, unregulated groundwater extraction (subchapter 2.3.5), intensification of agriculture (2.3.2) usually amplify rather than mitigate the factors responsible for overexploitation of available blue and green, renewable and fossil water, or increased soil loss (2.3.3). Overall, the uncertainties on the various subparts of the coupled man-earth system make it difficult to build, if not reliable, then at least realistic scenarios for the evolution of water and soil resources even for the coming decades. Like for GHG emissions, several ongoing projects under the AllEnvi umbrella try to identify a range of individual evolution scenarios based on actual mechanisms and hydrological models that are calibrated and evaluated using hydrological extremes extracted from recent history (2.3.1).



## Résumé

Ce chapitre présente les résultats de recherche concernant l'impact relatif attendu des changements anthropiques et climatiques sur les ressources en eau et en sols dans la région méditerranéenne, et leurs vulnérabilités associées. Les méthodes actuelles et leurs limites sont d'abord décrites dans le sous-chapitre 2.3.1. A travers l'élévation de température, les plus grand changements concernent l'évapotranspiration (plus grande demande climatique, stress hydrique plus fréquent) et les chutes de neige (moins de neige, la fonte se produit plus tôt), ainsi que la probable augmentation en nombre et en intensité des événements extrêmes (sécheresse, inondation, sous-chapitre 2.3. 2). Une menace particulière existe pour l'agriculture pluviale. L'impact sur l'érosion des sols des changements attendus dans la distribution des précipitations et les usages des terres est évalué dans le sous-chapitre 2.3.3. Le défi que constitue le besoin d'anticiper les impacts des événements précipitants extrêmes sur le risque d'inondation est documenté dans le sous-chapitre 2.3.4. La difficulté à maintenir une surveillance à long terme de ces ressources, avec peu de financements disponibles pour garantir un réseau de jaugeage suffisamment dense, nous encourage à développer des systèmes d'observation alternatifs, sur la base des données distribuées acquises par exemple par télédétection (2.3.2) ou à travers des enquêtes post-événement (2.3.4). Les activités humaines réduisent parfois certaines vulnérabilités (par exemple grâce à des ouvrages de conservation), mais amplifient le plus souvent les impacts négatifs du changement climatique sur les ressources en sols et en eaux: l'extraction non réglementée des eaux souterraines (sous-chapitre 2.3.5), l'intensification de l'agriculture (2.3.2) sont en général des facteurs aggravants plutôt que des facteurs d'atténuation pour la surexploitation de l'eau disponible bleue et verte, renouvelable et fossile, et participent de l'accroissement de la perte de sol. Dans l'ensemble, compte tenu des incertitudes sur les différents

sous-ensembles du système couplé Homme-Milieu, il est difficile de construire des scénarios fiables ou même réalistes pour l'évolution des ressources en eaux et en sols, même pour les prochaines décennies. Plusieurs projets en cours sous l'égide d'Allenvi proposent, de manière similaire à ce qui est fait pour les émissions de GES, des trajectoires limites basées sur les mécanismes à l'œuvre actuellement et des modèles hydrologiques calés et évalués sur les différents extrêmes climatiques identifiés pour des périodes récentes (2.3.1).

# Hydrological impacts of climate change in North African countries

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## Introduction

Countries in North Africa with a semi-arid Mediterranean climate are facing water scarcity and high inter-annual variability of their water resources. Many dams and reservoirs have been built in recent decades to collect surface water and improve the management of existing water resources (Figure 1). However climate projections for this region indicate a possible decrease in precipitation together with an increase in temperature that could result in increased evaporation (Schilling et al., 2012). Evaluating the potential impacts of climate change on water resources is thus of particular importance in this region. To quantify the impacts of climate change on hydrology, climate model outputs need to be combined with the outputs of hydrological models. Climate models provide simulations up to the year 2100, either at large scale (global circulation models) or at regional scale (regional climate models). Most climate models outputs cannot be used directly in hydrological models because the spatial scales do not match or because of a systematic bias in the model outputs, particularly for precipitation. Downscaling or bias-correction techniques thus need to be applied before making future hydrological projections. This chapter presents the main results obtained in the ENVIMED 'CLIHMAG' project funded by MISTRALS for the period 2014-2015. Three different issues are addressed: the validity of standard downscaling methods in a semi-arid context, the reliability of hydrological models in different climate conditions, and effect of the climate change signal on water resources in North African basins.

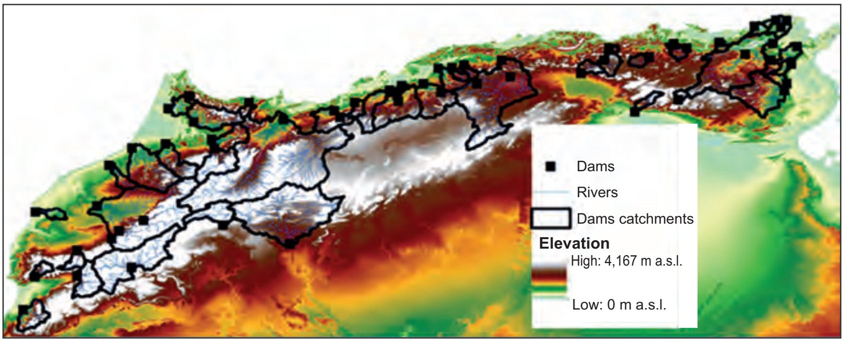


*Figure 1*
*Map of the 47 biggest dams in North Africa.*

The observed data needed to run the hydrological model used to address these issues came from a variety of representative catchments. These include the Loukkos (1785 km²) catchment, upstream of the Makhazine dam (the 6$^{th}$ largest dam in the country) in northern Morocco, the main tributary of the Oum Er Rbia basin, the El Abid (4980 km²) catchment, upstream of the Bin Ouidane dam (largest hydro-power production in Morocco), and in the high-altitude (up to 4167m) Rheraya catchment (225 km²) upstream of the Tensift catchment in southern Morocco. In Tunisia, the catchments selected are representative of the main hydrographical basins that produce most surface water resources. They include the Rhezala catchment (138 km²) in the Medjerda basin, upstream of the Sidi Salem dam (the largest in Tunisia), the Sejnane (376 km²), Joumine (231 km²), Melah (315 km²) and Maaden (145 km²) catchments in the north and Ichkeul basins and the El Abid catchment (81 km²) in the Cap Bon region.

## Are bias-correction methods for climate model outputs valid under semi-arid conditions?

Two kinds of climate simulations are available for studies on climate change impacts, general circulation models (GCM) running at a large scale (100-300 km) or regional climate models (RCM), driven at their boundary conditions by GCMs and running at the regional scale (12-25 km). In the Coordinated Regional Climate Downscaling Experiment (CORDEX, www.cordex.org), RCM simulations at a fine spatial scale (12 km) are becoming available for most regions of the world. North Africa is covered both by the EuroCORDEX and the MedCORDEX domains at a high resolution (12 km). This fine spatial scale allows orographic processes to be more realistically represented and improves the simulation of extreme rainfall events, which contribute a significant proportion of total precipitation in semi-arid areas. However, despite improvements in the models thanks to finer spatial resolution, precipitation is generally underestimated by models and cannot be used directly in hydrological models. For that reason, impact studies require downscaling and/or bias correction to reduce the gap between model outputs and observations, usually averaged or interpolated at the catchment scale for hydrological applications. A correction or a transfer function is often applied to climate model outputs, estimated in the past and applied to future simulations, assuming that the correction will remain valid in the future.

This rather strong assumption of stationarity of the correction applied to climate model outputs can be validated at least during historical periods; such validation has been performed for different catchments in North Africa. The results suggest that bias correction methods such as the quantile-mapping method, which is widely used in hydrological impact studies, may be difficult to validate in semi-arid climates due to the limited number of rainy days, in particular during summer, and to the significant inter-annual variability of precipitation, which is typical of the Mediterranean climate (Tramblay et al. 2013; Foughali et al. 2015). In the case of a shift towards drier conditions or different time periods, the methods may not be able to correct the model bias with sufficient accuracy, particularly for precipitation. If the bias correction methods are not properly validated using historical climate conditions prior to being used in future projections, this could affect the climate change signal. As an alternative to correction methods, other methods can provide climate scenarios based on the perturbation of the observed data series by a climate change signal.

A method that is commonly used for climate change impact studies is the change factor method sometimes referred to as the "delta change" method. It consists in modifying the observed data series (temperature, precipitation, etc.) by a climate change factor in order to produce climate scenarios (Tramblay et al. 2013). These types of methods range from simple ones that assume a monthly change factor, to more complex approaches perturbing the whole distribution of observations and resampling of the original sequences to account for changes in temporal variability. These methods do not rely on the stationary assumption of model biases and do not modify the climate model outputs. Consequently, they can be considered as more robust and should be preferred in cases where other approaches cannot be satisfactorily validated.

## Are hydrological models sufficiently robust to make future projections?

Different types of hydrological models exist that rely either on conceptual or physically-based structures. Physically-based models rely on the characteristics of the catchments and require many field observations, but these are rarely available, particularly in data-sparse regions and developing countries. Conversely, conceptual models usually require only time series of precipitation, evapotranspiration and discharge and are widely used in operational applications such as water resources or dam management. We tested a range of hydrological models (GR4J, GR2M, IHACRES, HBV, MWBM, BBH) commonly used for water resources management and research applications in North Africa under contrasted climatic conditions. Most hydrological models used in practical applications have a conceptual structure and require calibration (i.e. the model parameters are inferred using observed discharge data). However, calibration may be influenced by the choice of the time period of observations and therefore strongly impact the climate change projections.

The analysis of model robustness for the test catchments indicated that the difference in climate between calibration and validation gradually affect model performances. Although the model parameters tested were shown to be transferable towards wetter and/or colder conditions, their efficiency decreased when more contrasted climate conditions than those in the period used for calibration are experienced (for example in Tunisia, a threshold of transferability has been identified when the future change in temperatures exceeds +1.5 °C and the decrease in precipitation is more than -20%, Dakhlaoui et al. 2015). As a consequence, in studies on the impacts of climate change, we recommend choosing calibration periods when the climate conditions resemble future climate conditions, as this could significantly reduce hydrological modelling uncertainty.

## How will projected climate change affect water resources?

The projected impacts on water resources were analyzed using an ensemble of medium (50 km) and high (12 km) resolution simulations from the EuroCORDEX and MedCORDEX experiments. The multi-model ensemble composed of different RCMs driven by different GCMs made it possible to evaluate the uncertainties stemming from the different simulations. Two emission scenarios were used, the representative concentration pathways (RCP) 4.5 and 8.5. They describe future climates that are considered possible depending on the quantity of greenhouse gases emitted in the years to come. In RCP 4.5 emissions peak around the year 2040, whereas in the most pessimistic scenario (RCP 8.5), emissions continue to rise throughout the 21st century.

The results at regional scale confirmed those of previous studies indicating a general increase in temperature associated with a decrease in precipitation (Bargaoui et al. 2014). However, the high resolution simulations enabled better spatial characterization of the projected changes. As shown in Figure 2, the relative changes in precipitation follow a clear east-to-west gradient with precipitation projected to decrease by 10% on average in basins in northern Tunisia to a 40% decrease in southern Morocco. On the opposite, the projected changes in temperature are much more homogeneous over North Africa (Figure 3) and depend mainly on the different emission scenarios considered (RCP 4.5 and RCP 8.5). In addition, potential evapotranspiration is projected to increase (+10% to +30%) in most areas, these changes being modulated by both land cover and land use. As a consequence, reduced precipitation associated with increased evaporation leads to less surface water resources in all North African catchments in both scenarios. According to the multi-model ensemble, these changes are robust since all models agree on the same decreasing trend. The change in precipitation will have the strongest impact on water resources, since North African catchments are water-limited rather than energy-limited.

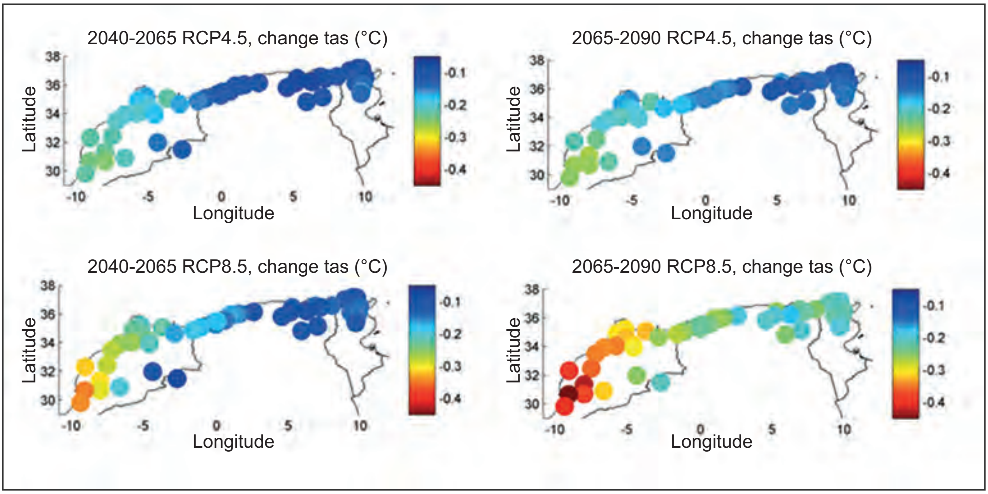


*Figure 2*
*Future changes in precipitation in the 47 main dam catchments in North Africa, simulated by the SMHI-RCA4 regional climate model driven by 5 global climate models (CNRM, IPSL, HADGEM, ECEARTH, MPI) under the emission scenarios RCP 4.5 and 8.5.*

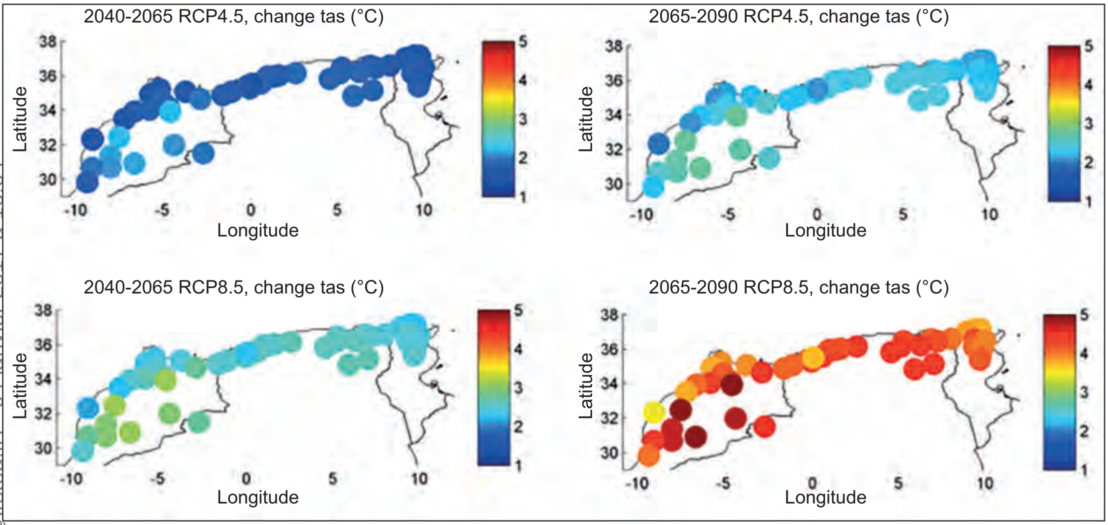


*Figure 3*
*Future changes in temperature in the 47 main dam catchments in North Africa, simulated by the SMHI-RCA4 regional climate model driven by 5 global climate models (CNRM, IPSL, HADGEM, ECEARTH, MPI) under the emission scenarios RCP 4.5 and 8.5.*

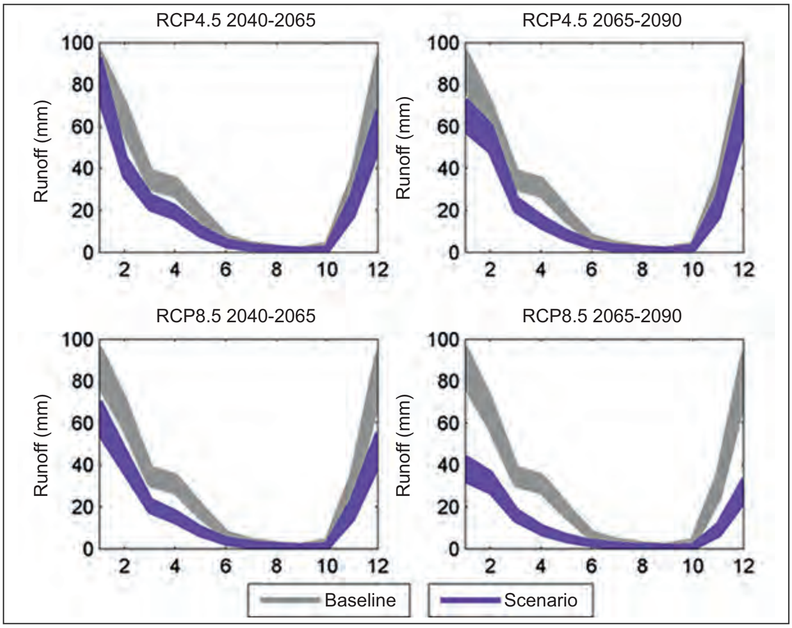


*Figure 4*
*Future changes in mean monthly runoff at the Makhazine dam (north Morocco). The band width indicates the uncertainty on model projections (simulated by the SMHI-RCA4 regional climate model driven by 5 global climate models: CNRM, IPSL, HADGEM, ECEARTH, MPI).*

We also analyzed the hydrological impact of the projected changes at the scale of the representative catchments considered in the ENVIMED CLIHMAG project. The results we obtained are illustrated by two examples of runoff projections presented for a catchment located in northern (Figure 4) and southern Morocco (Figure 5). For catchments located in the most humid areas, covering north Morocco, Algeria and Tunisia, the climate change signal is toward a reduction of 10% to 20% in precipitation, and as shown in Figure 4 for the mid-term time horizon (2040-2065), and in RCP 4.5, in most seasons, it is hard to distinguish between climate change, natural variability and modelling uncertainties. However in the most pessimistic emission scenario (RCP 8.5), the projected decline in surface water is significant in winter and spring. Conversely, in the snow-dominated catchments mainly located in the Atlas Mountains in southern Morocco (Marchane et al. 2016), a much stronger climate change signal points to a major decrease in spring runoff associated with a reduced snow cover (Figure 5). This could have serious consequences since these arid regions depend to a large extent on the water resources provided by the mountain ranges.

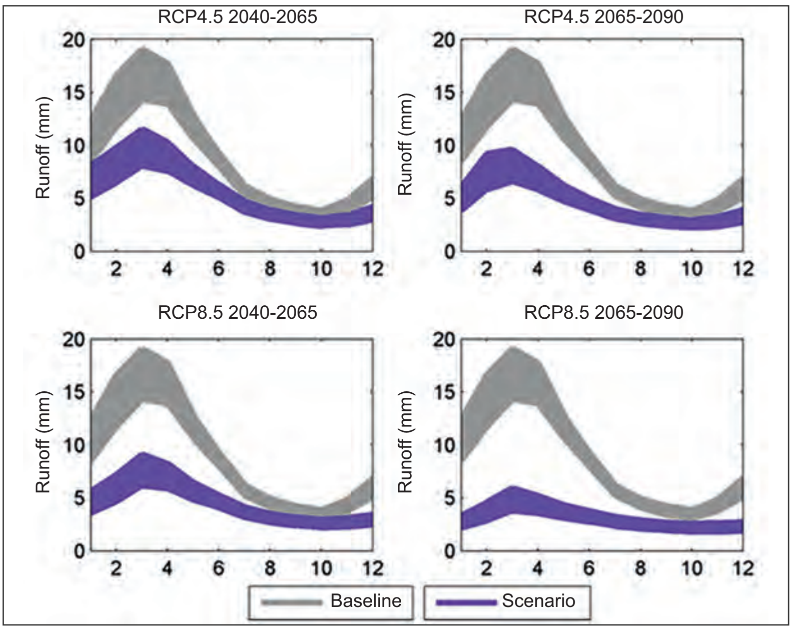


*Figure 5*
*Future changes in mean monthly runoff for the Bin Ouidane dam (south Morocco). The band width indicates the uncertainty on model projections (simulated by the SMHI-RCA4 regional climate model driven by 5 global climate models: CNRM, IPSL, HADGEM, ECEARTH, MPI).*

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Sub-chapter 2.3.2

# Water resources in South Mediterranean catchments

## Assessing climatic drivers and impacts

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## Climate change

Positive trends in mean temperatures and a decrease in the number and amplitude of cold outbreaks have already affected all North African countries (Driouech et al., 2013). A global data set of near-surface meteorological variables was used to assess the long-term changes in temperature and precipitation in North Africa in the 20$^{th}$ century (Szczypta et al. in prep). The analysis revealed a significant increase (0.9 °C) in mean temperature between 1900 and 2010 (Figure 1). The increase was larger in spring (+1 °C) than in winter (+ 0.4 °C), except over the northeastern part of the region, where the increase remained high (+ 1.2 °C) throughout the year. The observed change in precipitation was less homogeneous over space and time but identified a hot-spot in northern Morocco. In addition to the aforementioned historical study, under the RCP2.6 low emission scenario, projected warming should reach 2 °C to 3.5 °C (from the coasts to inland areas) by mid-century and under the RCP8.5 high emission scenario, 3.5 °C to 5.5 °C. This goes hand in hand with an increase in the mean annual number of hot days. The original climate scenarios have been downscaled for two local stations (Marrakech, Morocco and Kairouan, Tunisia) in order to debias the original model simulations. In the moderate emission scenarios, similar trends are highlighted locally with an average increase in temperature of 1 °C by 2030, and of up to 1.5 °C by 2050 for both Marrakech and Kairouan. This increase should affect the warmest months of the year the most. Over Morocco, the projected increase in evapotranspiration varies from 10% to 20% under the RCP8.5 scenario for the whole crop season and should be also higher in spring. At the regional scale, the change in precipitation is more uncertain due to an observed divergence between model simulations compounded by significant inter-annual variability. However, significant reductions in precipitation are projected over the northern parts of Algeria and of Morocco; the wettest and largest agricultural areas in the region. A decrease of about 15% to 20% is projected by the mid-century under the RCP8.5 scenario and more severe reductions are projected for the second half of this century. The reduction is projected to be the most pronounced in spring and fall with probably dramatic consequences for water availability in these key periods of the agricultural season.

## Anticipated societal changes

The population of southern Mediterranean countries will almost double by 2050, thereby threatening the fragile balance between water availability and human demand and, more specifically food security. At the 2025 horizon, agricultural demand could increase by 25% in response to the predicted population growth combined with the expected decrease in precipitation and rise in temperature at key phenological stages of crops in spring, while urbanization and economic development will encourage competition among sectors. The replacement of traditional Mediterranean crops (wheat) by more financially attractive crops but that also consume more water (maize, tree crops) will lead to major changes in water use patterns. In particular, the current extension and intensification of tree crops will further constrain agricultural water demand, especially during the hottest months. In addition, secure access to water from dams and water transfer channels is now threatened by dam silting and recurrent droughts like those at the beginning

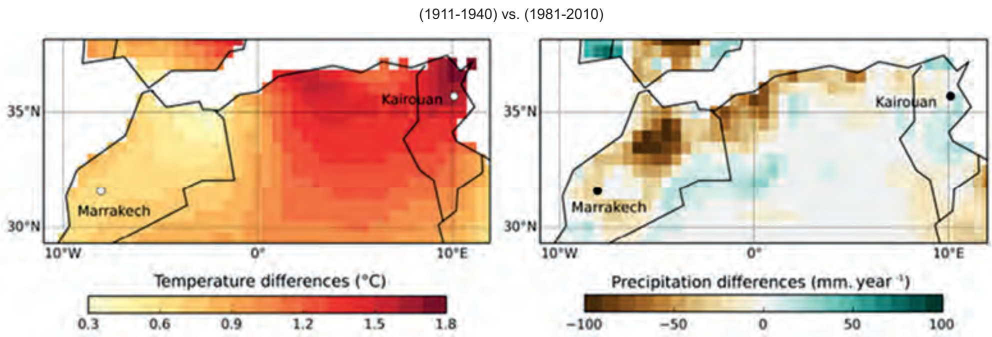


*Figure 1*
*Historical analysis: differences of mean temperatures (left)/precipitation (right) between 1911-1940 and 1981-2010 at a 0.5° resolution from the Global Soil Wetness Project Phase 3 (GSWP3) from Szczypta et al., in prep.*



## Box 1
## Observational issues

Long term observations are essential both for resource management and for hydrological model development and calibration over a wide range of climate conditions including extremes that are likely to become frequent in the future. Current water resources observation systems were thought to provide a good picture of available supply at the catchment outflow locations but are affected by loss of data quality, a decrease in the number of gauging stations, and the lack of available data since the 1980s. Upstream processes such as snowpack dynamics and subsurface flows that contribute to groundwater recharge, and downstream usage, are poorly monitored. Some integrated, long-term observatories of water resources that aim to complement the actual operational network exist, in particular in the Tensift and the Merguellil regions, but these successful initiatives need to be multiplied, strengthened and unified around an integrated regional observation system. Groundwater recharge processes (along *wadis*, by return of irrigation water, by subsurface flows or artificial through augmented streambeds) are currently largely unknown and should be the focus of scientific studies, in particular based on geochemical tracers. Non-conventional observations such as remote sensing and new innovative experimental designs based on low-cost *in situ* sensors should be promoted in these ungauged basins. Remote sensing will undergo a true revolution with the recent launch of the Copernicus constellation that will provide - free of charge - a large quantity of observations to enable monitoring of key variables for water resources management such as the extent of snow covered areas, soil moisture, land cover and use, surface water reservoirs, or crop dynamics. Despite the unprecedented availability of remote sensing data, their use by managers and stakeholders is still limited by their belief that the products are not suited to their specific needs. In practice, however, this is mostly due to lack of adequate training.

of the 2000s. As a result of the reduction in surface water, of agricultural extension and of easier access to water through boreholes (which are often neither registered nor monitored), groundwater is facing increasing pressure leading to groundwater depletion in the order of one to two meters per year with complete exhaustion at several locations. One of the potential consequences is farmer fragmentation resulting from the exclusion of small-scale farmers who do not have financial means to dig deeper and deeper wells. The intensification of agriculture in the plains may also increase societal tensions as the associated increase in water demand could become incompatible with the allocation of water to other sectors and with the ancestral water rights of upstream populations. Finally, the rapid pace of observed and anticipated societal changes are likely to have more effect on water resources than climate change in the medium term (2030), but the latter could have a greater impact at longer time scales.

## The water tower in the mountain range

Each winter, large amounts of water are stored as snow in the highest mountainous areas of the Mediterranean. In the Tensift region, up to 50% of runoff is attributed to snow melt. Due to already observed rise in temperature, the snowline is rising in the Tensift region, with less water being stored as snow. This could be associated with a more rapid transfer of a larger proportion of precipitation downstream, which could rapidly challenge the existing storage capacity. Due to the rise in temperature, melt rates are also increasing and the snow is melting earlier than in the past in lower elevation areas. Early melt and reduced snow storage further reduce low flow discharge, could increase the number of days the *wadis* are dry and threaten the use surface irrigation systems in particular for tree crops in summer. In addition, in contrast to rainfall, the slow release of water due to melting enhances infiltration over runoff and reduces the return of water to the atmosphere by evaporation. Sublimation, loss of snow that does not contribute to runoff, is usually small, but is subject to marked interannual variability (Boudhar et al. 2015); it is not yet clear if climate change (through changes in wind intensity and air humidity) will increase or reduce sublimation, while current best estimates are that can account for up to 20% of total snow loss.

A better understanding of the links between upstream and downstream processes is essential to enable water planning, as water use and the upstream supply can significantly affect water availability downstream. On the other hand, a change that occurs upstream can also sometimes address an issue that occurs downstream. Several key processes that contribute to groundwater recharge occur at the upstream/downstream interface since recharge of basin aquifers through direct infiltration of rainfall is generally limited, as observed in Tensift region (Boukhari et al. 2015). Population density and upstream water use is increasing with unmonitored uptakes along the river to irrigate agriculture in the foothills. The expected changes in the snow/rain partition and uncontrolled water uptake may directly affect the timing and amount of water available downstream as well as indirectly through changes in the groundwater recharge rates.



## Improving water irrigation planning

Although ambitious policies to convert to water saving techniques are currently being promoted, the traditional flood irrigation method, whose efficiency does not exceed 50%, remains the dominant practice in the southern Mediterranean. Improving this efficiency could be one way to tackle the expected reduction in water allocated to agriculture in the future.

Experimental studies on the main crops grown in the Mediterranean region (wheat, olives, oranges, etc.) carried out in the Tensift (Morocco) and Merguellil (Tunisia) regions called the efficiency of drip irrigation into question by showing that percolation losses from fields equipped with drip irrigation can equal and even exceed evaporation losses from flood-irrigated fields (Chehbouni et al., 2008; Jarlan et al., 2015). The lack of farmer training combined with the absence of complementary water regulation policies could thus have the unexpected consequence of increasing water losses for the plant. Another risk associated with conversion is agricultural intensification, which has already taken place in some locations and could also weaken or even negate the intended effect. Another important issue is related to the optimal choice of sowing date: fields in which the crops are sowed early would benefit from rainfall that is more effective at the beginning of the season and avoid the high evapotranspiration losses at the end of the season (April–May) which coincide with the grain filling stage of wheat, a critical stage for grain production. Modeling and experimental studies on wheat in Morocco revealed that the quantity of irrigation water required was always more than 100 mm (38%) higher in the case of late sowing. Deficit irrigation is also a promising technique but its implementation at large scales will be hampered by the lack of adequate tools for monitoring plant water stress plus it implies a drastic switch in irrigation planning from the existing supply-oriented system to a more plant demand-oriented system. A case study in Tunisia showed that irrigating cereals at 70% of their actual water requirement levels resulted in only a very slight drop in yield. Despite these encouraging results, farmer's awareness raising and training sessions will be needed for this technique to be widely adopted.

Targeted research work in Morocco and Tunisia aims to promote the use of remote sensing observations to monitor plant demand and water stress. The added value of a decision support system designed to plan irrigation has been successfully demonstrated in real-life conditions at the plot scale (Le Page et al., 2014). One of the main limitations to its implementation at a larger scale (i.e. that of an irrigated perimeter) are the many existing constraints to on-time water delivery: the network of concrete channels extensively used for modern irrigation sectors, requires the sequential application of water to parcels; the channel flow is limited; the workforce is also a constraint. Recent preliminary simulation studies demonstrated that water saving could reach 25% even in a highly constrained irrigated perimeter, if information on actual plant water demand is taken into account in the irrigation planning strategy (Belaqziz et al. 2014).

## Summary and conclusion

The executive summary of this chapter is as follows:

Global warming could increase freshwater water availability in spring during the transition period, and this should be taken into account in future watershed management policies. This could happen through increased snow melt and an already observed change in the rain/snow partition.

Long term monitoring of the water resource is of prime importance both for sustainable management and for model calibration. Given the weakness of existing *in situ* networks, remote sensing is an essential tool in these areas.

The groundwater depletion already observed in many southern Mediterranean catchments could negatively affect the poorest farming communities, who do not have financial means to deepen their wells.

Planning irrigation based on plant demand rather than the actual supply-oriented approach could enable substantial water savings even in the case of highly constrained existing modern irrigation systems.

Policies that promote water saving techniques including drip irrigation and deficit irrigation should be added to farmer training, control of water usage, and monitoring of agricultural intensification to fulfil the objective of saving water.

Foreseeing, monitoring and developing measures for adaptation to the expected changes requires an integrated catchment-wide approach to water management that brings together researchers and stakeholders. This requires building properly calibrated numerical modelling platforms, taking advantage of long-term observations including remote sensing data, to construct different scenarios of climate and anthropogenic changes (land use, irrigation methods, catchment planning) and their associated impact on water resources.

## Acknowledgements

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Sub-chapter 2.3.3

# Challenges for mitigating Mediterranean soil erosion under global change

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## Introduction

Soil is an essential resource that provides a wide range of ecosystem services (Dominati et al. 2010). Its formation is slow, but its destruction can be rapid. Soil erosion by water is a natural phenomenon that is impacted by human activities and global change. The long history of intense cultivation and a unique combination of relief, parent material and climate conditions makes Mediterranean soils and soil patterns very different from those in other regions in the world. Several studies have shown that, in the Mediterranean basin, current soil loss rates drastically exceed soil formation rates (Kosmas et al. 1997). In addition, an increase in intense precipitation events due to climate change is expected in the 21st century. For these reasons, suitable adaptive managing strategies for Mediterranean soils cannot be simply transposed from experiments conducted in other regions of the world. This paper presents the main lessons to be drawn and challenges involved in preventing soil erosion in the Mediterranean region under global change reported in the literature, plus results obtained in several research projects[1].



## Soil erosion in the Mediterranean basin

Mediterranean soils are particularly prone to erosion (García-Ruiz et al. 2013) because of (i) marked relief, 45% of the region has slopes greater than 8%, (ii) the high frequency of intense rainfall events (> 100 mm $h^{-1}$) in fall and winter, (iii) the presence of poor, shallow and skeletal soils, and (iv) sparse natural vegetation subjected to severe summer droughts. In addition to these natural drivers, intense cultivation even on steep slopes, burning, overgrazing and deforestation can greatly accelerate soil erosion, which, on the other hand, is limited by the many soil and water conservation measures (SWC) such as terracing in hilly areas.

The impacts of soil erosion can be divided into on-site and off-site effects. On-site effects are due to soil loss at field scale which, in certain extreme conditions, can lead to a net loss of cultivated area. This quantitative soil loss impacts agricultural production through the loss of nutrients, soil water reserves, and alterations to soil properties. Soil erosion also has significant off-site effects through the delivery of sediments to rivers, which affects the mobilization of water by siltation of reservoirs, and reduces the quality of water destined for irrigation and drinking.

Higher sediment yields (SY) than in many other regions have been measured in the Mediterranean basin (Woodward, 1995). These were often explained by the high contribution of gully and riverbank erosion processes (Vanmaercke et al. 2012). Gullies and especially badlands have been identified as a major source of sediments involved in siltation of reservoirs in the Mediterranean region (De Vente et al. 2006). The majority of SY occur during a few extreme rainfall events ("time compression", González-Hidalgo et al. 2007). However, these generalities mask huge variability across the basin as a whole. Based on a dataset containing 104 cumulated years of continuous SY measurements in eight small catchments ranging from 0.15 to 1.3 $km^2$ in size (Figure 1), Smetanova et al. (submitted) show that (i) the annual SY varied between 0 and ~27100 $t \cdot km^{-2} \cdot yr^{-1}$; (ii) catchments display two main contrasted patterns of SY seasonality; (iii) time compression is highly variable from one catchment to another. Ben Slimane et al. (2015) demonstrated that the predominance of gully and riverbank erosion processes in the Mediterranean basin was site dependent and not as widespread as previously thought.

1. http://www.agence-nationale-recherche.fr/?Projet=ANR-06-VULN-0012, http://www.obs-omere.org/, http://jeai-vecteur.org/, http://www.sicmed.net/#/projets-projects/3778554https://sites.google.com/site/rosmedsicmed/, http://jeai-vecteur.org/

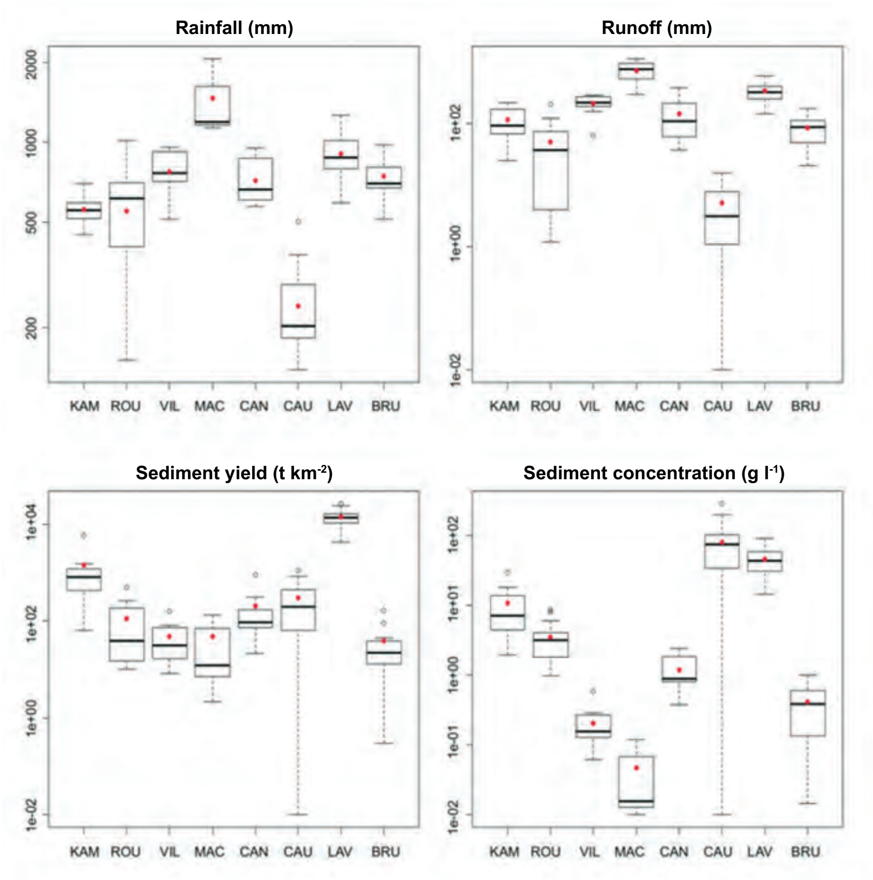


*Figure 1*
*Range of intensity of erosion processes in the Mediterranean basin illustrated through inter-annual variability of rainfall (mm), runoff (mm), sediment yield (SY) ($t \cdot km^{-2}$) and sediment concentration ($g \cdot l^{-1}$) observed in 8 catchments of the R_Osmed network: KAM (Kamech, Tunisia), ROU (Roujan, France), VIL (Can Vila, Spain), MAC (Macieira de Alcôba, Portugal), CAN (Cannata, Italy), CAU (El Cautivo, Spain), LAV (Laval, France), BRU (Brusquet, Spain). Inter-annual means are plotted as red circles.*

# Expected future changes in Mediterranean soil resources under global change

Climate change will have both direct and indirect effects on soil erosion. Direct effects are due to changes in the amount, erosive power and spatio-temporal pattern of rainfall. Global change model projections indicate that longer droughts and more frequent extreme precipitation events are likely to occur.

Because of the high degree of SY time compression, the increased frequency and intensity of the largest events will increase soil erosion. The soil system reacts non-linearly to such changes, so even small increases in rainfall amount or intensity can dramatically increase soil loss rates. Climate change could also lead to a temporal shift in both the vegetation cover and the rainfall pattern that could positively or negatively indirectly affect erosion rates: the decline in surface runoff (which triggers erosion) could be partly counterbalanced by reduced biomass growth. Soil erosion could also be strongly affected by changes in land use and management due to human drivers (e.g., technological changes, demographic and socioeconomic trends and governance structures). Indeed, land use and management controls both soil characteristics and the distribution of overland flows. Some widespread crops, including vineyards and olive groves, and practices such as extensive overgrazing in mountain areas are known to encourage erosion. An increase in land abandonment and forest fires because of global change could also increase erosion in young fallows and post-fire conditions.

In the MESOEROS21[2] project, the impact of changes in rainfall characteristics and land cover on the risk of soil erosion in the Mediterranean basin was evaluated using a set of erosion models on (i) small and medium size gauged watersheds in France, Tunisia and Morocco, and (ii) the Mediterranean basin as a whole. The models were parameterized using measurements from highly gauged catchments and applied to the largest basins to calculate present and future conditions. Climate changes were estimated from global general circulation simulations and adapted to local conditions. Several land use change scenarios were built, including an «Accentuation » scenario in which both cultivated and natural vegetation are degraded, and a « Protection » scenario in which natural vegetation and good practices in cultivated area are favored. Two main results of the project (Paroissien et al. 2015; Simonneaux et al. 2015, Cerdan et al. 2011) were:

1) Simulating soil erosion rates is difficult because of the marked spatial and temporal variability of the processes involved and the uncertainty associated with the input parameters;

2) Land use is the main driver of changes in erosion risk and soil vulnerability in the Mediterranean basin.

2. Mediterranean Soils EROsion and vulnerability to global change during the 21$^{st}$ century

# Main challenges for the future of Mediterranean soil resources

## Toward a better knowledge of the factors and processes involved in soil erosion

Despite the increased availability of spatially distributed data, model application is still hampered by the low quality of input data. We therefore need to make better use of recent techniques to complete the too sparse legacy soil data to capture short scale soil variations in the Mediterranean basin and to improve our knowledge of future conditions to design efficient adaptation techniques. Long-term catchment erosion monitoring systems and Mediterranean networking initiatives are ideal ways to obtain a good picture of the variability of erosion processes and to explore the specific role of major/extreme events or sedimentological connectivity involved in sediment yield (SY) variability.

## Toward the evaluation of soil risk

There is a need for a scientifically sound yet simple index of the risk of soil erosion that combines erosion rates and vulnerability and can be readily understood by decision makers. When assessing soil erosion vulnerability, it is important to consider the soil as a patrimonial resource that combines several basic soil functions (e.g., soil fertility and carbon storage) but also cultural and civilizational values related to religion, livelihood and health (Minami, 2009). The choice and valuation of criteria to be used for SE vulnerability are however complex issues, especially in the Mediterranean basin where for example, vineyards or olive trees can grow in soils that would be considered as very degraded using standard criteria. Even when the focus is on a very simple criterion such as soil depth as in Paroissien et al. (2015), soil vulnerability to erosion is difficult to estimate because soil depth is neither a standard, nor an easy, measurement.

## Toward site specific conservation strategies

Mediterranean civilizations have successively developed or improved a wide range of techniques to improve water conservation and management, increase agricultural production, and reduce soil erosion. These techniques mainly concern correcting the slope/ reducing water velocity (e.g. through terraces), increasing ground cover (e.g. through the use of cover crops), restoring rangelands, and/or improving soil quality (e.g. through amendments). Recently SWC techniques have extended to sustainable land management or conservation agriculture that favor less soil disturbance, using crop residues as mulch, continuous ground cover, and crop rotations or associations. The efficiency of no-till conservation agriculture in increasing topsoil soil organic content and improve the soil water storage is widely recognised in the Mediterranean basin (Mrabet, 2011). However, these techniques

Box 1

## Challenging issues for mitigating Mediterranean soil erosion under global change

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Raindrops control detachment directly through their impact on the soil matrix and indirectly through runoff, which is generally related to the decrease in infiltrability as a direct consequence of the degradation of the superficial structure under the action of rain (Moore and Singer, 1990). Rain also plays a role in particle transport: either in transport caused by the impact of drops, or in transport flow caused by raindrops (Kinnel, 2005). Looking at detachment by raindrops in more detail, it turns out that the rain actually controls two distinct successive processes: 1) the disintegration of particles at the surface and 2) the motion of the fragments produced by disaggregation by splash effect. Rain therefore plays an important role both in the total mass of eroded soil and in the size of the particles set in motion (Legout et al., 2005). Rainfall is usually directly measured by rain gauges but these only provide local and partial information for the scientific issues we want to address.

The first issue concerns the appropriate descriptors for rain (the diameter and number of drops, rain intensity and kinetic energy, and so on) that influence the erosion processes: they are not yet well defined and no consensus has yet been reached in the scientific community. It is consequently necessary to diversify measurements of rain to identify which factors concern erosion. A disdrometer is an instrument used to measure droplet size distributions and the values of other descriptors of rain. This instrument was used during laboratory experiments of detachment with rainfall simulators generating different intensities and energies. These experiments confirmed that the strongest kinetic energies were associated with the largest detached masses. It was also demonstrated that the strongest energies detached the largest proportions of fine particles (that are more easily mobilized by runoff). These observations were confirmed on 120 m² erosion plots under natural rainfall.

The second issue concerns the spatio-temporal structures of rainfall that lead to significant hydro-sedimentary responses. To address this issue, access to spatialized information with high temporal frequency is required. Although weather radar provides indirect measurements, it fulfils this requirement. It is a complementary observation tool that is all the more useful as Mediterranean rainfall can be very localized and last only a very short time (often a few minutes).

Several observation systems are available to deal with these issues including "ORE Draix" in the Southern Alps, "SNO OHMCV" in the Cevennes and "ORE OMERE" for Kamech watersheds in north eastern Tunisia. These observatories have hydro-sedimentary devices for the measurement of suspended sediments, sometimes sediment traps, and precipitation devices (rain gauges, disdrometers, sometimes radar) in various hydro-climatic and soil-use contexts.

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have varying degree of success depending on the environmental and societal contexts (García-Ruiz, 2013). Maintaining a continuous land cover may for instance have positive impacts on soil protection but negatives ones on production because of competition for water in semi-arid areas (Marques et al. 2010). In the end, the benefit of each technique needs to be checked in site-specific conditions, especially in Mediterranean areas where the complexity of the landscape results in significantly diverse contexts. Lessons from past changes in the Mediterranean environment through a review of adaptation techniques already experimented and a site by site evaluation of their soil protection efficiency and acceptability by local farmers will be helpful. Many mitigation strategies cited above are based on profound changes in agricultural practices. The massive introduction of such strategies in existing Mediterranean agrosystems is a challenge, and will have to take the specificities of each agrosystem into account, along with its socio-economic and environmental dimensions, and be supported by local or national policies.

# Conclusions

Mediterranean soil resources are crucial for the social and economic development of the region but their sustainability is threatened by intense erosion processes, which have severe on-site and off-site effects. However, the nature and intensity of active erosion processes are as varied as the mosaic of Mediterranean landscapes. Realistic maps of soil erosion risk, vulnerability and sustainability cannot be produced without knowledge of erosion factors and processes acquired in awareness of this diversity.

When we modeled future soil degradation and catchment sediment delivery, the direct impacts of climate change alone were found to be lower than the impacts of changes in land use or in land management. The first challenge is thus to better forecast future changes in land use/management changes, whether or not driven by climate. The second challenge is to propose a strategy to anticipate projected changes and to mitigate their impacts. A wide range of adaptation or mitigation techniques exists and many have already been tested in the Mediterranean basin. It is now important to evaluate their efficiency and acceptability in the wide range of site-specific conditions. This will require new integrated approaches able to combine (i) quantitative and qualitative impacts of soil erosion; and (ii) natural and anthropogenic factors and processes.

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Sub-chapter 2.3.4

# Inter-disciplinary post-event surveys to disentangle hazard from vulnerability in the impacts of Mediterranean flash-flood events

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## A matter of space and time scales

Heavy precipitation events (HPE) and flash floods (FF) are common phenomena over the Mediterranean region. The peculiar topography and geographical location of this area make it especially favorable to the occurrence of intense events. The Mediterranean Sea acts as a vast heat and moisture reservoir from which baroclinic atmospheric systems pump part of their energy. The steep orography surrounding the Mediterranean Sea favors lifting of the low-level unstable air and initiation of condensation processes. Although they occur in well-known synoptic conditions, these intense rainfall events result from complex interactions between the atmosphere, the sea and continental surfaces. Mesoscale processes (orographic forcing, but also deflection and convergence of air masses, formation of cold pools and down-valley flows, etc.) lead to a variety of convective systems ranging from orographic rainfall events, thunderstorms, to the most dangerous stationary mesoscale convective systems (MCS) (Bresson et al. 2012). Despite recent progress due to the assimilation of mesoscale meteorological data in highly resolved numerical weather prediction models, the predictability of thunderstorms and MCSs remains quite low both in terms of intensity and localization.

Moreover, the morphology of the Mediterranean basin with its numerous small and steep river catchments and increasing urbanization of the coastal zones trigger very rapid hydrologic responses. The subsequent FFs are very dangerous for the exposed populations. A clear link exists between the hydrologic response (fig. 1) and the size of a watershed subject to a HPE. Typical times to peak can be as short as 10 min for urban watersheds of 10 km², and as short as 1-2 hours for natural basins extending from some tens to some hundreds of km² in mountainous settings. The time to peak spans a range of about one order of magnitude for a given watershed surface, showing that the hydrological responses also depend on other factors, such as topography, geology, land use, storm intensity and initial soil moisture. There is also a relationship between the space-time scales of the generating rainfall events (fig. 1) and the hydrologic response. This supports the concept of "scale resonance", e.g., a thunderstorm is likely to generate FF events over urban basins of some tens of km² while a stationary MCS is required to produce FFs and floods over watersheds of 100-2,000 km². Regional floods (e.g. Rhône River floods) are associated with frontal systems with much larger spatial extension and temporal duration.

Regarding the coping capacity of the exposed societies, the concept of "timeliness of flood anticipation" was proposed by Creutin et al. (2013) to describe how a sequence of anticipatory actions (known as the IOP sequence, for Information, Organization, Protection) is synchronized with the development of the flood. The situation is particularly tense in the Mediterranean context due to the limited predictability of rainfall and the rapid hydrological responses. Exposed individuals may experience a wide range of hazard conditions with different timeframes, depending on the size of the upstream watershed where they are located. The most critical situations are likely to occur at the finest spatial scales. Ruin et al. (2008) demonstrated that the majority of casualties that occurred during the 2002 Gard event in France happened in watersheds of less than 50 km².

As a detailed complement to the regional analyses proposed by Gaume et al. (2016) (subchapter 1.3.4), in the following sections we provide illustrative results obtained from inter-disciplinary post-event surveys (PES) aimed at understanding the complexity of both the hydrological responses to HPE and the behavior of the exposed populations during such sudden crises. So far research on

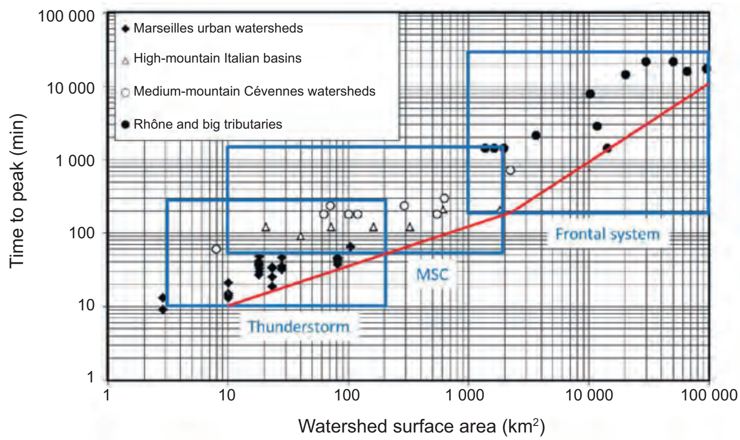


***Figure 1***

*Hydrological response of Mediterranean and Alpine basins expressed in terms of the time to peak (delay between the hyetograph centroid and the flood peak) as a function of the surface area of the watershed. The red lines define the envelope curve of the shortest times to peak, critical information for warning and crisis management. The blue rectangles show typical space-time scales of the generating rain events.*

hydrological and social systems has proceeded in "separate boxes" without many contacts between research disciplines (Parker et al. 2012). The consequence is that neither physical nor social sciences have acquired a comprehensive overview that would enable improvement of event response. We believe that the PES approach is needed to disentangle the respective contributions of hazard and human vulnerability to the impacts of flash-flood events, notably the causes and dynamics of casualties.

# Complexity of the hydrologic response to extreme precipitation events

The recent development of weather radar networks opens new perspectives for the characterization of the space-time variability of the generating rainfall events. Weather radars provide rainfall estimates at appropriate resolutions, typically (1 km², 5 min). However, rain gauge data remain a critical source of information to constrain radar data processing algorithms and/or to validate the radar estimations. Bouilloud et al. (2010) proposed a pragmatic method for dealing with two main physical errors of radar, namely those due to the interactions between radar waves and the relief and those due to the vertical structure of the rain systems. Geostatistical methods proved to be optimal for merging corrected radar data and rain gauge data (Delrieu et al. 2014) by removing the bias of radar estimates while retaining their enhanced perception of the spatial variability of rainfall.

Hydrological PESs aim to collect three types of data (Gaume and Borga 2008; Marchi et al. 2009):

(i) Peak discharge estimates over ungauged upstream basins; this is done by performing cross section surveys (cross section and energy slope estimation using flood marks) complemented by clues concerning flow velocities (e.g., video recordings, water super-elevations in front of obstacles, etc.).

(ii) Indicators of the time sequence of the flood (time of peak(s), dynamics of the flood rise and recession). For ungauged sections, this information is obtained from eyewitness accounts.

(iii) Indicators of sediment transfer processes (erosion and deposition in the river beds, mud or debris flows) as an indication of the runoff processes, flow energy and velocity. This is particularly relevant in high mountain settings (Borga et al. 2014; Rinaldi et al. 2016) where such processes create specific risks and affect both the landscapes (soil conservation) and the rivers (channel instability, reservoir filling, etc.).

Figure 2 illustrates the results of the PES conducted after the disastrous flood event that affected the Gard region on September 8-9, 2002 (Delrieu et al. 2005; Bonnifait et al. 2009). This disaster (24 casualties, 1.2 billion euros) was due to an MCS system that remained stationary for 28 hours and produced more than 200 mm rain over an area of 5,500 km², and which locally reached more than 700 mm. The green insert in figure 2 shows the added value obtained from the PES in terms of documenting the peak discharges for ungauged basins (< 100 km²). The specific peak discharges reached extreme values (40 $m^3s^{-1}km^{-2}$) at the smallest spatial scales investigated (1-10 km²). The blue insert gives three examples of rainfall-runoff time series for upstream ungauged watersheds. The hydrographs were produced with a hydrological model constrained by the estimated PES discharges and checked with the reconstructed time sequences obtained from the PES. Note that different rainfall-runoff scenarios can be observed locally with single and double peak discharges, fully explained by the displacement of the MCS during the event. At the outlet of one of the main rivers (red insert), the distributed hydrological model was too reactive; coupling with a 1D hydraulic model was necessary to represent the control exerted by the Gardon Gorges. The latter resulted in major flooding of the upstream plain, thereby protecting the city of Remoulins from an even more disastrous flood, an interesting example of geomorphological control on medium-scale flood. The hydraulic model also showed that the operational rating curve of the gauging station available prior to the event largely overestimated the discharges, an example of the marked uncertainties affecting flood discharges even in gauged stations. Other factors that determine the hydrological response are the initial soil moisture status and the geology (Vannier et al. 2016). Frequently advocated factors such as deforestation, poor river bed maintenance and even urbanization are likely to play a marginal role in the case of heavy rainfall events when the storage capacity of the soils is fully saturated.

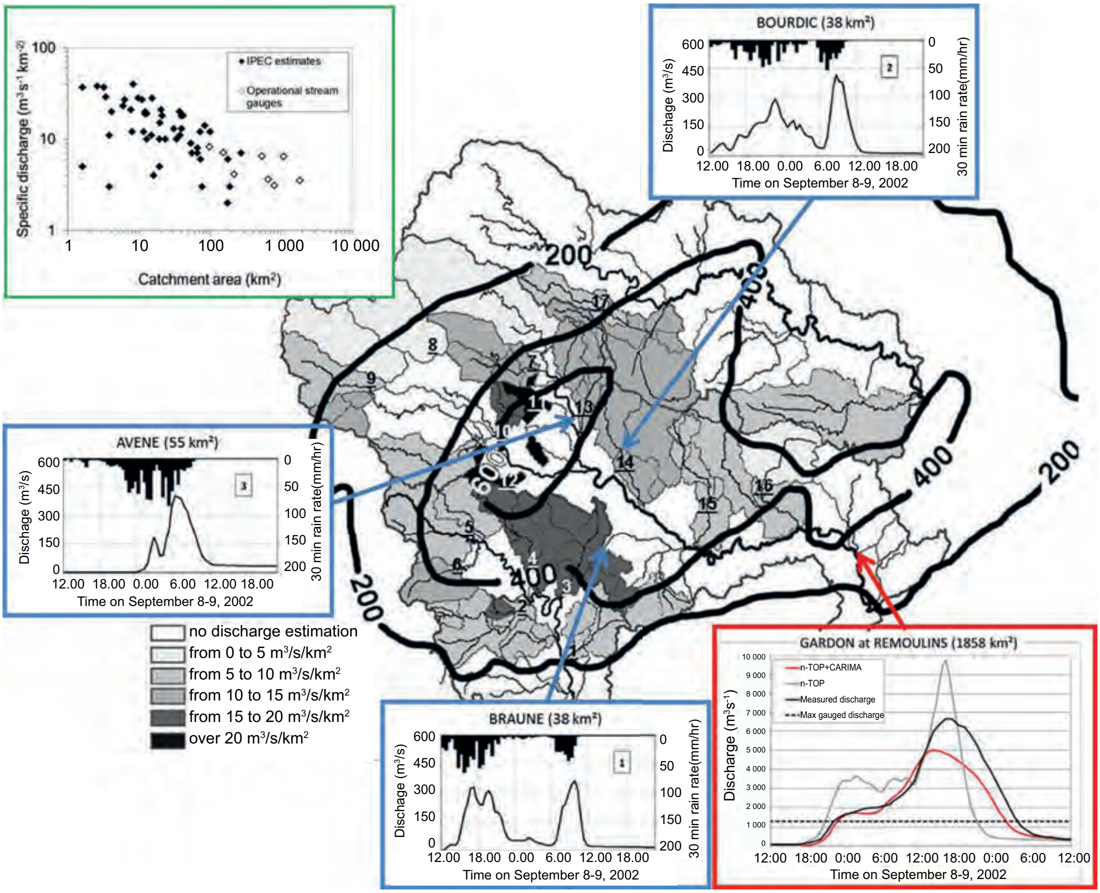


*Figure 2*
*Illustration of the hydrological response complexity of the Gard event in France on September 8-9, 2002. The map shows the rainfall isohyets (contours of 200, 400, and 600 mm of rain) superimposed on the river network of the affected area. The sub-watersheds are colored as a function of the maximum specific discharges estimated during the PES. The green insert shows the maximum specific discharges estimated during the PES for ungauged catchments as well as those derived from operational gauging stations as a function of the surface area of the watershed. The blue inserts give 3 examples of the response of small upstream watersheds. The red insert shows the hydrologic/hydraulic response at the outlet of the Gardon watershed at Remoulins.*

# How do individuals cope with flash floods?

The social PES aims to collect behavioral, temporal and spatial information related to changes in the environmental conditions and activities in which people are involved prior to and during the crisis. Its objective is to document how individuals switch from routine activities to emergency coping behaviors. It is structured around a chronological guideline with which interviewees are invited to recall what they perceived from their environment, what actions they undertook, and with whom they interacted in different places and while moving in between places. The survey campaign starts by interviewing the contact people identified during the hydrological PES. These people are also asked to recruit other interviewees with whom they were directly or indirectly in contact at various stages of the event. This snowball sampling technique makes it possible to collect diversified and complementary information.

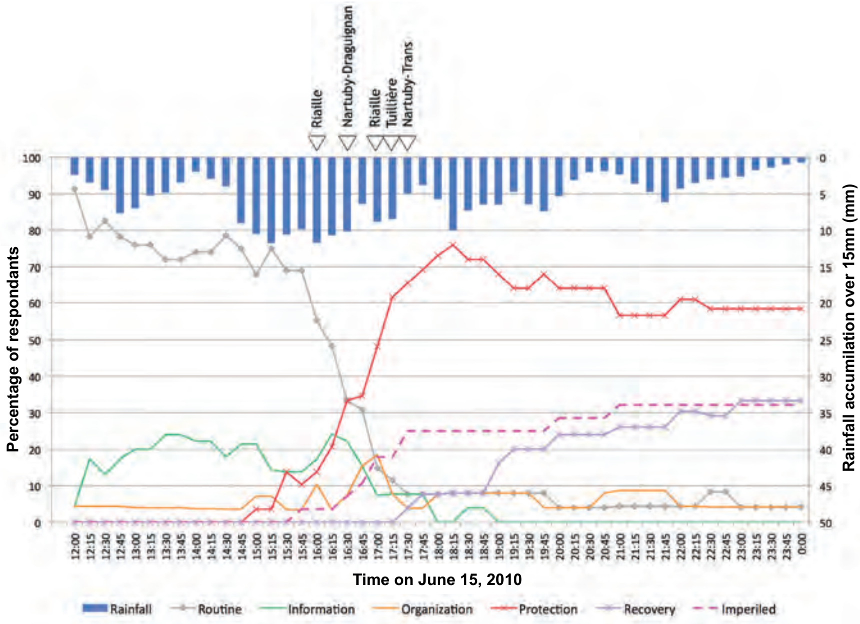


*Figure 3*
*Changes in behavioral responses of the social PES respondents during the FF event on June 15, 2010 in Draguignan, France, in terms of routine activity, awareness of the crisis through information, organization, protection and recovery actions. The cumulative percentage of imperiled people during the event is also shown. Note the rapid drop in routine, information, and organization curves to the profit of the protection curve between 15:30 and 17:30 which corresponds to the danger outburst (peak flows, generalized surface runoff). The orange vigilance warning launched by Météo France the preceding day and the TV news at midday reached only a limited proportion of respondents (20%).*

This approach was first used after the June 15, 2010 FF event in the Var region, France (Ruin et al. 2014) which was responsible for the deaths of 26 people. Data collection efforts concentrated on three municipalities located on the Nartuby River. Figure 3 shows the proportion of interviewees as a function of the type of activity over time, together with rainfall intensity and the times of peak flood in the corresponding watersheds.

This social PES allowed us to identify some possible causes of the individual responses. The possible conflicts of priority between routine and exceptional circumstances explained the difficulty in switching from daily activities to responding to warnings. The difficulty in making sense of environmental cues in the case of insufficient official warning also emerged as a possible cause of delay in individual responses. Because FF environmental conditions vary tremendously across space in very short periods of time, it is often difficult for those who are affected to fully grasp the situation in which they find themselves or to imagine the variability of the threat moving across space. The study also revealed a form of the individual's self-organization and the emergence of helpful social interactions that may involve different types of social ties. Finally, this case study confirmed the role of contextual factors (Parker et al. 2009): the timing of the hydro-meteorological event, its severity, and experience of the flood appear to be essential in the ability of individuals to make sense of the situation and to adapt their activities.

# Conclusions

As a complement to regional analyses (Gaume et al. 2016, sub-chapter 1.3.4), we believe such inter-disciplinary post-event surveys are indispensable for the mitigation of FF events in the Mediterranean because they allow a better understanding of the causative hydrological processes and the subsequent social responses in different climatological and social contexts around the Mediterranean Sea. Due to their heavy death toll, so far, the focus has been on short-term crisis management with the aim of increasing people's preparedness through education, and improving the efficiency of warning and alert systems. Obviously, long-term management of this type of natural hazard also involves socio-economic considerations related to land planning and controlled urbanization, a particularly difficult topic in the context of the increasing human pressure and the expected climate change in the Mediterranean region.

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Sub-chapter 2.3.5

# Changes in Mediterranean groundwater resources

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## Introduction

The strong variability in space and time of all components of the hydrological cycle is a fundamental feature of the Mediterranean region (e.g. Cudennec et al. 2007). Its most visible marker is the succession of droughts and floods that deeply affects environment and societies. Impacts of such events on groundwater are obvious but there are countless drivers of hydrological changes that act under multiple forms.

Among them, irrigation is of primary importance. For millennia, Mediterranean populations developed strategies of adaptation to water scarcity and exploited groundwater to secure crops against seasonal and interannual irregularity in rainfall and river flows. Ancient Mediterranean civilizations have left many traces of their hydraulic mastery from the tapping and transfer of spring water to the drainage of aquifers or the digging of deep wells (e.g. Remini et al. 2010).

But the 20th century represented a complete disruption because technical advances allowed massive access to groundwater. Irrigation now represents between 50% and 90% of the total Mediterranean water demand (UNEP/MAP-Plan Bleu 2009) and has based its "silent revolution" on intense groundwater exploitation. This has led to critical drops of groundwater levels of up to several hundred meters in a few decades (e.g. Custodio et al. 2016). Many other human interventions have consequences for groundwater quantity and quality including changes in land use and land cover, hydraulic works, artificial inflows and outflows. These often interact at different scales of time and space, which makes the current state of groundwater a complex combination of multiple processes.

## Original features of groundwater resources

Sedimentary aquifers are by far the largest regional reservoirs in the Mediterranean region. Most are small or medium in size, i.e. a few hundreds or thousands of square kilometers. They represent the last stage of an eventful geological history that still influences the present, especially active tectonics and variations in sea level since the Miocene. The apparent opposition in water circulation processes between fissured carbonates and porous media often plays a secondary role in comparison with more important properties like storage capacity and resilience to external stresses.

The first driver of their recharge is the heterogeneous distribution of rainfall, which is largely influenced by topography, particularly apparent by the contrast between relatively humid hinterlands and drier littorals. Recharge depends mainly on the intensity and distribution of rainfall events in space and time, and on vegetation and soil surface conditions: monthly and annual amounts of rainfall are only insignificantly linked with the real recharge reaching aquifers. The role of water towers played by upstream areas is illustrated by the Haouz plain of Marrakech whose groundwater originates from upstream catchments and not from direct infiltration of rainfall over the plain (Boukhari et al. 2015). The weakness or even complete lack of diffuse recharge and the major role of focused recharge are very common in the Mediterranean region.

Groundwater also comes from exchanges with rivers, especially during the highest floods. Depending on the event, infiltration can vary by one or two orders of magnitude. This implies that aquifer dynamics has to be analyzed simultaneously at several scales, from the event up to the millennium: the largest confined aquifer systems contain information dating back to the last humid period in the Holocene (e.g. Zuppi and Sacchi 2004).

Because of climatic surface conditions, a regional geology rich in carbonates and evaporites, and easy contact between the sea and the littoral aquifers, Mediterranean groundwaters are often highly mineralized. For instance, only one fifth of Tunisian groundwaters have a salt content lower than 1.5 $g.L^{-1}$ while another fifth exceed 4 $g.L^{-1}$ (Besbes et al. 2014). A significant proportion of the theoretically available Mediterranean groundwater resource is in fact not exploitable for human use without treatment.



# Climatic change and groundwater

Apart from the few last centuries when direct observations have been made, climatic variations are reconstituted from proxies. As humans have been highly active in the Mediterranean for millennia, it is necessary to disentangle the climatic and human origins of apparent modifications of the socio-environments in the Holocene, and also to differentiate local and regional phenomena. Temperature reconstructions in the north-western part of the Mediterranean region by Camuffo et al. (2010) indicates that past cycles already reached current measurements. The resulting sea level rise is a potential threat for littoral aquifers, but far behind the threat represented by their modern exploitation. Regarding past variations in rainfall, the wide range of proposals in the scientific literature mirrors the wide range of data, methods and objectives of the authors concerned. According to careful analyses (e.g. Reiser and Kutiel 2011) no coherent regional trend can be identified over the 20$^{th}$ century. At a longer perspective of several centuries, some consistencies and also significant discrepancies appear in climatic reconstructions between eastern and western sub-basins or even between north-western and south-western sub-basins.

In recent decades or centuries, spectacular events that may have marked infiltration are attributable to the usual great variability of the Mediterranean climate. And today, the multiple forms of anthropization of the hydrological cycle completely dwarf the climatic signal.

# Anthropization of groundwater resources

Expansion of irrigation highly exploits groundwater resources whatever their renewal rate. Cases of severe overexploitation are numerous and widespread throughout the region: in Libya, the demand for water for irrigation is about ten times higher than renewable water resources. Even worse, overexploitation in fragile aquifers leads to rapid social and environmental disasters like in the coastal Chaouia of Morocco (Moustadraf et al. 2008). But cases also exist where the development of irrigation leads to an increase in the superficial groundwater resource because of a significant return flow of excess irrigation water, pumped from deeper aquifers or imported by large channels, like in the Spanish Cartagena aquifer (e.g. Baudron et al. 2014) or the Moroccan Tadla aquifer (e.g. Bouchaou et al. 2009).

Changes in water consumption for irrigation are far more influenced by technical (e.g. drip systems), economic (e.g. energy cost), social (e.g. local knowledge) and political (e.g. subsidies) drivers than by increasing temperatures modifying crop water demand. There is evidence for a wide range of illicit but tolerated groundwater exploitation practices in many Mediterranean countries, which are sometimes even encouraged by national authorities. Two emblematic cases are widespread unauthorized boreholes and unauthorized plants for desalinating brackish groundwater.

Apart from irrigation, agriculture modifies land uses and land covers in many ways (areas covered by rangelands, forests and fields; crop intensification; etc.) that modify the proportion of blue and green water, and consequently the flux and location of groundwater recharge.

Hydraulic works are another major component of the modification of the groundwater regime, either by a direct impact or by an intermediate effect on surface water that subsequently modifies recharge. Hydraulic works include a very wide range of sizes and construction modes from big and small dams to soil and water conservation works, and traditional bench terraces. Their number considerably increased in the 20th century, and only a very few of them were built with the explicit intent of modifying recharge (e.g. Martin-Rosales et al. 2007), probably less than cases of unexpected losses that contribute significantly to new groundwater inflows (e.g. Leduc et al. 2007). The efficiency of the recharge of these different hydraulic works varies considerably over time, depending on siltation, maintenance, etc. This non-exhaustive list can be completed with pumping and refuse from quarries and mines, losses of long distance water transfer, drainage of wetlands, plots for artificial recharge, etc.

Groundwater is also intensely exploited for the supply of drinking water, which has rapidly increased as a consequence of population growth, the improved ratio of the population supplied, and higher standards of living. The concentration of population in Mediterranean coastal areas results in an ever increasing demand for drinking water in areas where groundwater of good quality is often naturally rare and sources of quality degradation numerous (e.g. seawater intrusion, waste water). To the fundamental priority of drinking water is added the provision of groundwater for tourism and industry, which are usually present in the same areas as cities and increase the spatial and temporal disequilibrium of groundwater exploitation.



## Consequences of changes for groundwater

Anthropization of the Mediterranean environment directly affects the location, temporality and intensity of groundwater fluxes in both recharge and outflow (e.g. limitation of floods in alluvial plains, increased vertical fluxes under irrigated schemes, leakage inversion). It also affects groundwater quality, in nearly all cases leading to its degradation: increased mineralization of water stored for a longer time at the surface before infiltration (e.g. in irrigated fields, in dam reservoirs), pollution by fertilizers and pesticides used in agriculture, advance of seawater intrusion, uncontrolled discharge of wastewater, artificial mixing of groundwaters in defective or multiscreened boreholes, etc. The qualitative consequences of groundwater anthropization are often less perceptible (i.e. less visible and/or less surveyed) than drops in groundwater level, which partly explains the inertia of decision makers before implementing costly remediation actions that have to be continued over long periods.

The progressive superseding of natural processes by anthropized ones increases the complexity of both hydrodynamics and geochemistry, at multiple scales of space and time (Fig.1). The consequence should be a supplementary effort to densify survey and analysis whereas in practice, most observation networks have worsened under financial constraints in the last two decades. Some are no longer appropriate for the new emerging issues, and large territories remain almost unknown.

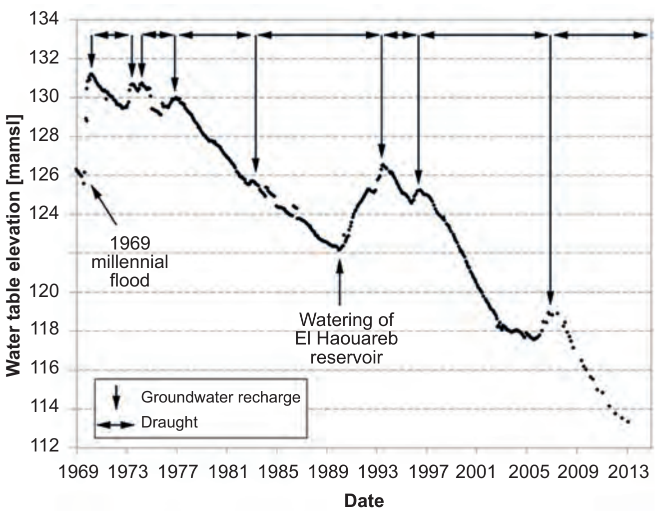


*Figure 1*

*Changes in the water table depth in the Kairouan plain. The two biggest rises are due to the catastrophic floods in 1969 and the construction of the big El Haouareb dam; other rises due to wet years are much smaller. But the major trend is the severe long term drop caused by the ever increasing pumping for agriculture.*

The capacity of water managers to inform their decisions with groundwater knowledge diminishes with time, in parallel with the higher pressure on groundwater resources, the higher vulnerability of socio-hydrosystems, and the much stronger claim of citizens to play an active role in the decision process. In addition to individual requests, collective welfare and long-term sustainability must also be taken into consideration. This is particularly important for environmental water demand, often taken as an adjustment variable, and sacrificed to needs that are considered to be more urgent, at the risk of causing irremediable damage. This addresses the more general issue of the role of states and their ability to enforce law.

The rapid evolution of Mediterranean socio-environments is a major challenge for scientists and managers. The intricacy of technical, societal and biophysical drivers is progressively increasing and taking new forms. Among these multiple drivers, climate change currently has less impact than many other drivers. Whatever their relative importance in the future, beyond traditional disciplinary and/or technical studies, holistic approaches will have to be developed, and anticipating major crises will largely depend on our ability to imagine possible futures outside traditional thought frameworks. Most Mediterranean groundwater resources have been considerably reduced in quantity and degraded in quality in recent decades, preserving their resilience capacity is an absolute necessity to withstand the projected increase in the frequency of extreme events.



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Chapter 4

# Impacts on terrestrial biodiversity and ecosystems

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## Abstract

This chapter explores four selected aspects of the influence of climate change on Mediterranean land ecosystems. First, it explores the interaction between climate change, changes in land use, and the functioning of Mediterranean forests from the human perspective (Gauquelin et al.). Mediterranean forests are characterized by exceptional biodiversity, with 290 woody species and numerous plants and animals depending on them. Most of the trees are evergreen, adapted to some level of drought stress, but deciduous trees are also present. Many forests are actually open woodlands. Mediterranean forested landscapes therefore display high spatial heterogeneity, offering multiple functions for associated wildlife, as well as for human recreation. Risks to the functioning of these forests originate not only from climate change but also from destruction and unsustainable use.

In some forested sites this situation can now be considered typical of many Mediterranean ecosystems, and raises the question of their stability, or resilience

(Mouillot et al). Experimental treatments now make it possible to test the degree to which increased drought, for example, may have longer-lasting impacts on ecosystem function than simply a potentially temporary reduction in growth and productivity.

The Mediterranean is a large archipelago with approximately 10,000 small and large islands that alone explain a significant part of its biodiversity (Médail et al.). While these islands are subject to similar forcings i.e., warming, drought, land use change and sea-level rise, the local impacts differ strongly from place to place. One group of species with particular climate and local habitat requirements are orchids (Schatz et al.). Analysis of the few existing long observational series of these orchids makes it possible to distinguish between the most and the least sensitive groups, but more research is needed to develop predictive tools to assess future risks to them.

## Résumé

Dans ce chapitre, on présente quatre aspects spécifiques des effets du changement climatique sur les écosystèmes continentaux. Tout d'abord, les interactions entre le changement climatique, les changements d'usage des sols et le fonctionnement des forêts méditerranéennes selon une perspective sociétale (Gauquelin *et al.*). La biodiversité des forêts méditerranéennes est exceptionnellement riche, avec 250 espèces ligneuses et de nombreuses espèces animales ou végétales qui en dépendent. La plupart des arbres sont sempervirents, adaptés à un certain niveau de stress hydrique, mais il existe aussi des espèces décidues et de nombreuses forêts sont aujourd'hui des forêts ouvertes. Ainsi, les paysages forestiers méditerranéens montrent une grande hétérogénéité spatiale, ce qui profite à la faune sauvage et leur confère un aspect récréatif. En plus du changement climatique, leur destruction et leur utilisation de manière non durable pèsent également sur les forêts méditerranéennes.

Dans le cas de sites forestiers considérés comme caractéristiques de nombreux écosystèmes méditerranéens, les questions actuelles sont celles de leur stabilité ou de leur résilience (Mouillot *et al.*). Certaines expériences permettent de tester avec quel degré une sécheresse prolongée peut par exemple impacter le fonctionnement de l'écosystème sur le long terme, au-delà d'une simple réduction temporaire de la croissance et de la productivité.

La Méditerranée est un large archipel avec environ 10 000 îles grandes et petites, ce qui explique une part significative de la biodiversité méditerranéenne (Médail *et al.*). Alors que ces îles sont toutes confrontées au réchauffement, à la sécheresse, aux changements d'occupation du sol et à la remontée du niveau de la mer, les impacts locaux diffèrent grandement selon les régions. Des espèces

comme les orchidées manifestent des besoins particuliers en termes de climat et d'habitat (Schatz *et al.)*. L'analyse de quelques séries d'observation sur le long terme permet de distinguer différents groupes d'orchidées, plus ou moins sensibles. Cependant, des recherches supplémentaires sont nécessaires afin d'établir des outils prédictifs permettant d'estimer les risques futurs qu'ils encourent.



## Introduction

Mediterranean land ecosystems are among the richest in the world. Located near one of the world's regions of origin of human agriculture and civilization, they have evolved in close interaction with human society over several millennia. Direct human impacts have consequently been very strong and visible, in the form of deforestation, the development of agricultural landscapes, gardening, soil degradation, urbanization, and (during the last century or so) air and water pollution, the arrival of alien species and the protection of some areas for conservation. Some of these impacts have reduced biodiversity, while others have enhanced it.

Despite these direct impacts of humans on biota, the highly specific Mediterranean climate remains one of the key determinants of the biodiversity and ecosystem structure in the region. Hot summers regularly lead to dry conditions in much of the basin, requiring little extra stress to cause biomass loss or dieback in a number of species. Mild humid winters provide the right conditions for high biological productivity. Warming is currently occurring faster in the Mediterranean than global averages, and affects land ecosystems in several different ways. First, direct heat stress may occur during heat waves in summer. Winter warming can be beneficial, but may also alter interactions with pests or alien species that find better conditions for survival and then have a negative impact on plant growth and survival. However, changes in water availability are more important than warming, and are the primary cause of productivity losses during the summer season, notably during dry spells which are tending to become longer. Reduced access to water is also an issue in the southern and eastern parts of the basin during winter, a tendency that will be exacerbated in the future. Remarkably, while global climate models still exhibit much regional uncertainty in terms of rainfall predictions, they all agree on the expected reduction in rainfall in the Mediterranean region. This enhanced drought has effects on all ecosystems, whether managed or unmanaged. In agro-ecosystems some potential for adaptation through irrigation exists, but is limited by the generally limited availability of water resources for irrigation, and also due to the limited economic potential in southern and eastern Mediterranean countries to pump and distribute more water to the fields. Finally, climate change also influences land ecosystems through the sea-level rise which can cause “coastal squeeze”, in which circumstances no space is available for coastal ecosystems to move to higher areas, and notably by affecting coastal wetlands such as the Camargue, the Nile Delta and other similar areas.

Sub-chapter 2.4.1

# Mediterranean forests, biocultural heritage and climate change

## A social-ecological perspective

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# Mediterranean forests, unique ecosystems?

A Mediterranean forest is defined as a forest growing under a Mediterranean climate characterized by a marked rainfall deficit in summer that causes the vegetation stress (Gauquelin 2011). Forests in the Mediterranean basin cover more than 48.2 million ha of which 35 million are located in southern Europe, 8.8 million ha in the Middle East and 4.4 million ha in North Africa (adapted from Quézel and Médail 2003; Fady and Médail 2004). The seasonality of air temperature and precipitation, which is the most distinctive feature of Mediterranean-type climates, has major implications for vegetation functioning, as it limits the active growing season to the humid period between fall and spring (Blondel and Aronson 1999). This period ranges from 5 to 10 months according to distinct climatic subtypes.

## Structure and biodiversity

As reported by EEA (European Environment Agency, 2006), evergreen and sclerophyllous plants, usually but not exclusively represented by deciduous forests, are particularly common in humid and perhumid bioclimates, underlining the complexity of forests in the Mediterranean basin (Quézel and Médail 2003). In the Mediterranean region, the term "forest" does not always refer to high, dense stands of trees with a closed canopy, and three main forest types (forest *sensu stricto*, pre-forestal structure and pre-steppic structure) can be distinguished (Quézel and Médail 2003) according to tree density and height.

The Mediterranean basin (*sensu lato*: 2% of the Earth's surface) is one of 34 identified biodiversity hot-spots (Médail and Quézel 1997; Benabid 2000). Mediterranean forests include 290 woody species versus only 135 for non-Mediterranean Europe, including a large number of endemic species (e.g. *Tetraclinis articulata*, *Argania spinosa*, *Juniperus thurifera, Quercus suber* and fir species such as *Abies pinsapo, Abies marocana*, *Abies nebrodensis*; Blondel et al. 2010) and high genetic diversity (see Fady 2005 for conifer species) with high levels of genetic originality in refugia (Médail and Diadema 2009).

## Functioning

The specificity of Mediterranean forest ecosystem functioning (phenology, primary and secondary plant metabolism, carbon storage, productivity, water cycle, redistribution of nutrients and microorganisms activity) is linked to the long period of drought, with highly discontinuous functioning linked to alternating dry and wet periods. In these conditions, phanerophyte evergreen and sclerophyllous species dominate, but are not the only type, and deciduous forests, mainly oak forests, are also well represented, particularly in humid and per-humid bioclimates, underlining the complexity of Mediterranean forests (Quezel and Medail, 2003)

Mediterranean plant species produce numerous plant secondary metabolites (PSMs), most of which are terpenoids (volatiles) and phenolics (non-volatiles). PSMs, together with morphological traits (sclerophylly), allow these species to cope with climatic stress (Chaves and Escudero 1999). Plant investment in PSMs affects numerous ecosystem function processes and biodiversity (Fernandez et al. 2013, 2016; Chomel et al. 2014).

Decomposition of organic matter, a key process for forest functioning, is also determined by the period of drought. Controlled by biotic factors such as decomposers (bacteria, fungi, invertebrates), and by the biochemical composition of the plant litter (i.e. plant diversity; Santonja et al. 2015a), this process is linked to the environmental conditions, particularly soil water content under a Mediterranean climate. Marked dry summer periods result in a discontinuous decomposition process that is closely linked to water availability (Chomel et al. 2014). The diversity of mycorrhizal fungi present in these ecosystems is crucial, as these symbiotic fungi are belowground linkers between plants that facilitate their host plant's access to soil nutrients (Barto et al. 2012) and to the soil water compartment.

Widely spaced trees, mainly in pre-forestal and pre-steppic stands, have a major impact on forest functioning (Joffre and Rambal, 1988; Gauquelin et al. 1992), leading to the very marked spatial heterogeneity. In man-made ecosystems characterized by a savannah-like physiognomy, e.g. the *dehesas* and *montados* of the Iberian Peninsula, scattered trees lead to high spatial heterogeneity in ecosystem functioning.

## Dynamics

Ecosystem dynamics on the southern and northern shores of the Mediterranean basin are quite different (Gauquelin 2011). The northern shore is characterized by coastal urbanization and the abandonment of agricultural and pastoral land, leading to spectacular forest re-colonization; for example, in the French Mediterranean area, between 1980 and 2011, forest covering more than 1.4 million ha increased by between 0.5% and 2% a year (IF 2013; FAO 2013), which corresponds to approximately 16.000 ha a year. On the southern shore, degradation is still intense and is causing the fragmentation or disappearance of different habitats including forest, with for example, an annual decrease of 0.5% in Algerian forest between 1990 and 2010 (FAO 2013).

# Mediterranean forests: a long history of agro-sylvo-pastoral management by rural populations and interactions between local societies

Most forests in the Mediterranean region are the result of a long history of agro-sylvo-pastoral management by rural populations and of interactions between local societies (Blondel 2006, Aubert 2013). In spite of the strong influence of local management practices and socio-political relationships on the *production* of Mediterranean forests, most studies insist on the *negative impact* that local societies have had on "natural forests" and on their biodiversity (deforestation, forest degradation and desertification). In contrast, Michon et al. (2007) analyzed the *co-evolution* between forest ecosystems and their related human populations in terms of *domestication* (of trees, ecosystems and landscapes), and considered the resulting forests (*domestic forests*, or *rural forests*; Genin et al. 2013) as biocultural, or socio-ecological products for agroforestry systems like those found on the Iberian Peninsula (Joffre et al. 1987, 1999).

Mediterranean forests have been, and in certain regions, still are, intensively used for rural livelihoods. They provide a wide range of resources including human food, medicines, ritual material, firewood, construction wood and forage for livestock. These forests are characterized by different levels of formal and informal appropriation by rural communities and are shaped by specific, refined knowledge and practices.

# Mediterranean forests and climate change

Climate models predict increases in both temperature and drought conditions in the Mediterranean (Schleussner et al. 2016). These changes are expected to increase the frequency, intensity and duration of drought, especially in summer (IPCC, 2014; Polade et al. 2014). The response of Mediterranean forests to such extreme climatic events is poorly understood, because conducting controlled field experiments to mimic such conditions is costly and difficult at a large scale without introducing environmental modifications. Different *in natura* platforms have been implemented in different types of forest in France, with rain exclusion devices that make it possible to apply a precipitation scenario close to the projections made by models for the end of the 21$^{st}$ century. Holm oak at Puechabon (Limousin et al. 2008, 2009, 2012), Aleppo pine at Font Blanche (Gea-Izquierdo et al. 2015) and downy oak at $O_3$HP (Santonja et al. 2015b) have been the subject of such experiments. Results showed that changing rainfall patterns will (i) directly affect the production and decomposition of litter (Santonja et al. 2015b,), and (ii) the emissions of volatile organic compounds (Staudt et al. 2002, 2003; Genard et al. 2015). There is a plan to set up a network of experimental stations around the Mediterranean basin with simpler and less expensive devices to monitor the effects of climate change on other important forest ecosystems and under other bioclimates.

Recent studies in northwestern Africa reported recurrent drought events from the second half of the 20th century on (Touchan et al. 2010; Linares et al. 2011; Kherchouche et al. 2012, 2013; Slimani 2014). Touchan et al. (2008) showed that the 1999-2002 drought was the worst in northwestern Africa since the middle of the 15th century. This suggests climate conditions are limiting for tree growth and affect the geographical distribution of drought-sensitive species, especially those at the edge of their range. The 1999-2002 drought event triggered substantial mortality in *Cedrus atlantica* forests where, in some areas, stands disappeared completely (Zine El Abidine 2003; Linares et al. 2011; Kherchouche et al. 2012, 2013; Slimani et al. 2014), and even in other tree species reputed for their drought hardiness, including *Pinus halepensis*, *Quercus ilex*, *Quercus suber*, *and Juniperus thurifera* (Allen et al. 2010).

Extreme climatic events could cause major disruption of Mediterranean forest functioning, increasing soil erosion, the frequency and intensity of forest fires, and pest outbreaks (Moriondo et al. 2006; Lindner et al. 2010). These disturbances will put a number of important ecosystems services at risk (Schröter et al. 2005). In this context, new ways of increasing the resistance and resilience of Mediterranean forests need to be developed, including those that harness the full potential of Mediterranean forest genetic resources (Lefèvre et al. 2014). Favoring mixed pine-hardwood species stands is increasingly proposed as a strategy to enhance forest resilience (Pausas et al. 2004). But it is also important to prepare the future of managed stands by careful selection of species in their optimum site conditions favoring more resilient species to future climate and making them less vulnerable. Partial thinning of some stands to limit competition is a solution to be recommended in some cases potentially linked with the wood energy sector, as well as protection against fire in the case of degraded stands at risk of desertification.

# Conclusion: reconciling particular ecological functioning, biocultural heritage and threats

Linking different elements allows us to propose an integrative and original outlook for Mediterranean forests:

– Linking basic and applied research: exploiting all scientific results should enable the identification of a successful strategy for the preservation and development of Mediterranean forests. Knowledge of the different levels of biodiversity could help preserve Mediterranean forests. At the species level, genetic diversity studies and the adaptive potential of a given species could help understand its reactions to environmental change. At the community level, understanding interactions between different species could lead to dramatic changes in reforestation practices. For instance, identifying the mycorrhizal community of some trees used in reforestation programs and the nurse effect of some shrub species on these trees could optimize large scale reforestation programs that take climate change into account, reduce the cost of watering and increase the success rate of these plantations. On the other hand, climate modelling applied to species distribution and genetic exploration of marginal populations can help predict shifts in species range and reduce the conservation actions required.

– Linking hard sciences, humanities and social sciences: understanding Mediterranean forest ecosystems and their future must first integrate 1) the secular human-forest interactions that have shaped functional cultural landscapes, and 2) the ecosystem services provided by these forests to secure both overall diverse ecosystems and livelihoods.

– Linking forestry, agricultural and social approaches and objectives: forests and the human populations living in and from these forests have to be protected in a global, comprehensive approach that takes both biological and cultural diversity into account. This requires truly participatory methods (i.e. not forcing local populations to participate in projects designed by foresters or biologists that aim at preserving forests *per se*, but conducting negotiations in which all stakeholders have a say).

– Linking the northern and southern Mediterranean: the forest structure, dynamics and threats are very different on the two shores of the Mediterranean and comparing the different situations is indispensable to understand the overall evolution of Mediterranean forests in the context of climate change.

– Linking "nature" and productive systems: particularly in the Mediterranean basin. This link refers to the continuum between "wild" and highly anthropized ecosystems that needs to be better understood to detect forms of uses able to guarantee the sustainability of these sensitive forest ecosystems and that of local livelihoods.

Mentioning the need for these links may sound like "praying for a miracle" since it has little to do with what is happening today. It is also difficult to report true "success stories" in developing productive "biocultural" approaches, i.e. combining ecological and cultural approaches for a better understanding and management of Mediterranean forests, as these two approaches are generally barely connected. Foresters, biologists, local populations and social scientists need to join forces to define a desirable "state of conservation" for Mediterranean forests, one that takes flora, fauna, and ecological services as well as local knowledge, practices, and production, into account. Practical measures to achieve, monitor and maintain this state will have to be invented, mobilizing scientific as well as local indicators of "degradation", regeneration practices, protection measures, for example combining the protective enclosure methods of foresters or *agdal* (a traditional forest management system in the Moroccan High Atlas) practices of local populations). This can only be done if local populations are included in the definition of conservation management objectives from the very beginning. The same global model can be mentioned for cork oak forest, formerly a "cultural forest" in the northern part of the Mediterranean basin that was "naturalized" after local cork oak management practices were abandoned, and that is currently severely affected by forest fires. Conservation of the cork-oak forest may reactivate local farmers' interest in ecosystem management that combines cork, pastoral and agricultural production. Such management models still exist in Spain and in the southern Mediterranean basin and could inspire the rehabilitation of abandoned cork oak forests in the North.

The aim of this brief synthesis was to highlight both the risks faced by Mediterranean forest ecosystems, and the opportunities they represent for sustainable development including for humans and human activities. The idea is to consider 2100 not only from the point of view of projected climate change but also possible changes in land use and socio-economic aspects, and to make proposals in this direction.

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Sub-chapter 2.4.2

# Mediterranean ecosystems facing global change

## Resilient or close to tipping point?

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## Introduction

Mediterranean-type ecosystems (MTEs) cover a small fraction of the terrestrial component of the Earth, and their functioning is driven by a recurrent summer drought concomitant with the hottest temperatures. Climate projections by general circulation models (GCM) under RCP 6.0 and 8.5 scenarios collectively forecast substantial drying and warming in regions surrounding the Mediterranean Sea, especially in summer (Schleussner et al 2016). MTEs are expected to be highly responsive to global climate change (Giorgi 2006) as a result of a change in large-scale circulation conditions (Kjellström et al. 2013), together leading to 1) increasing temperatures and decreasing rainfall (Hoerling et al. 2012), 2) the persistence of heat wave anomalies (Jaeger and Seneviratne 2011) and 3) longer, more intense and earlier drought periods (Ruffault et al. 2014). In this context, the fate of MTEs depends on their ability to withstand, adapt or recover from different disturbing forces, particularly drought. In addition, human impacts, an intrinsic aspect of MTE functioning, can increase, accelerate, or mitigate direct climate impacts, through forest management, setting fires or extinguishing fires, a significant process in MTEs. We assessed the short and long term resilience of MTEs to increasing drought as affected by direct climate forcings, and explored how similar drought trends driving fire risk, the major disturbance in MTEs, can lead to contrasted extents of burned area depending on local socio-economic features.

## Theoretical framework for ecosystem stability assessment under climate change: resilience vs. tipping point?

Reyer et al. (2015a) reviewed different approaches used to study the response of forests systems to anthropogenic global changes, to understand their capacity to recover from disturbances. These authors' underlying hypothesis is based on resilience theory, suggesting that forests might be able to tolerate disturbances and maintain their functioning and structure only up to a critical threshold. A slow rate of an ecosystem's recovery from a disturbance might be an early signal that its status is close to tipping point, a set of conditions under which a minor change leads to a major change in the state of the system. Among the most pertinent environmental drivers that predispose water-limited ecosystems like MTEs to tipping points are a reduction in rainfall amounts, especially in the dry season, an increase in temperatures, an increase in the frequency of extreme events, intensifying fire regimes, emerging invasions, pathogens and pests (Laurance et al. 2011). Using resilience theory, we assessed the current (in)-stability of an evergreen broadleaf forest (*Quercus ilex*), an ecosystem covering 6 Mha in the Mediterranean basin. The remotely-sensed MODIS normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI), two indicators of green canopy functioning, were used to test the recovery of the ecosystem from successive disturbances between 2000 and 2013, including the peculiar 2003 heat wave, a pest attack in 2005 (gypsy moth defoliation), and a severe drought in 2006. Both the NDVI and EVI were affected in 2005 and 2006, but a quick recovery was observed after 2007 followed by a stable trajectory even during the dry years 2009 and 2010, supporting the hypothesis of a high stability of this ecosystem. We further analyzed local ecosystem functioning to disentangle the mechanisms enabling such high resilience.

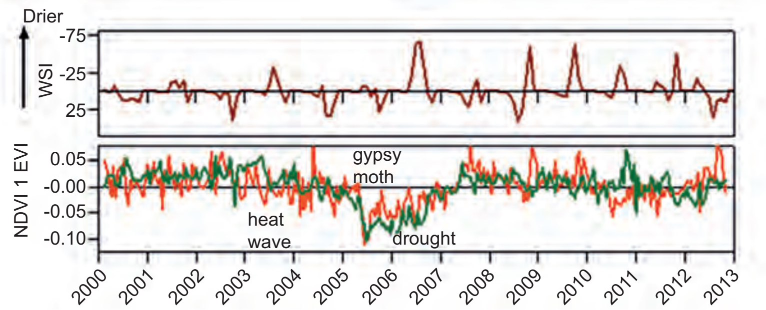


*Figure 1.*
*Time series of anomalies of MODIS 8 day composite NDVI and EVI over the evergreen broadleaf ecosystem surrounding the Puéchabon study site. The green line represents the NDVI and brown line the EVI. The time course of the Water Stress Integral anomaly expressed in MPa. day showing the recurrence of dry years in 2003, 2006, 2009 and 2010 is also plotted.*

We used the approaches proposed by Rustad (2008) to assess MTE resilience to increasing drought across the Mediterranean basin:

i) Long term observations in space and over time can be made at a single site, using networks of sites, and more recently, using global networks of sites such as Fluxnet (Luyssaert et al. 2009). Long term monitoring provides both deep insights and background information on ecosystem responses to short term "pulses" in weather and long term changes in climate (called a "press" constraint).

ii) Climate gradient studies are performed across geographical gradients and can exploit "space-for-time" substitutions for long term studies.

iii) Experimental manipulations (on climate drivers, and management strategies that affect the whole ecosystem) make it possible to study some cause and effect relationships and provide a mechanistic understanding of short term responses of ecosystems to one or more drivers of climate change and/or disturbance regime.

## Comparative resilience analysis from a throughfall exclusion experiment (TEE) and climate gradient on a *Quercus ilex* monospecific coppice

The Puéchabon study site (43°44'30"N, 3°35'40"E, elevation 270 m, France), an intermediate dry site on the drought gradient of the *Quercus ilex* distribution (figure 2), offers a spectrum of ecosystem scale measurements and manipulative experiments that includes water, energy and carbon fluxes since 1998 and a throughfall exclusion experiment (TEE) monitored continuously since 2003. In the TEE, the control treatment receives ambient precipitation and the dry treatment is subjected to partial throughfall exclusion (-27% precipitation by means of PVC gutters suspended under the canopy). Each treatment plot covers 100 m$^2$ and each treatment is replicated three times (for a more detailed description of the TEE, see Limousin et al. 2009).

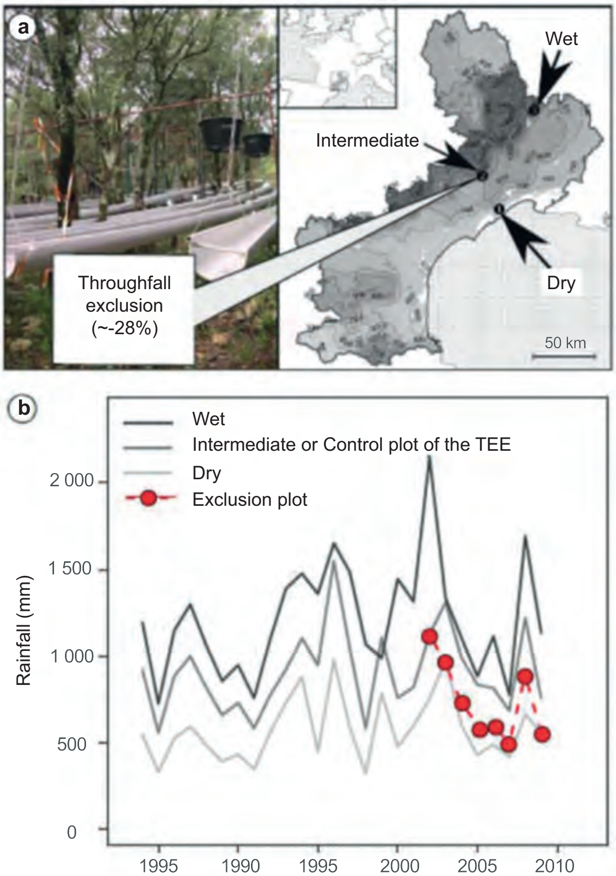


*Figure 2*
*Location of the partial rain exclusion experiment in the Puéchabon TEE in southern France (top right panel). a) PVC gutters intercept 27% of rainfall under the tree canopy in TEE (top left panel). b) Regional rainfall gradient (annual rainfall at the wet study site, TEE and dry study sites are presented for the period 1983-2009).*

The main results of the TEE after 13 years of experiment are presented in table 1. Increasing drought primarily led to a rapid loss of leaf area (-22%), which in turn reduced photosynthesis (-14%), litter fall (-21%) and carbon loss through autotrophic (-14%) and heterotrophic respiration (-11%). The loss of leaf area had a negative impact on tree and ecosystem carbon balance but, by concomitantly limiting transpiration by -23%, maintained the soil water content at a level similar to that in the control plot, and subsequently similar drought timing, length and intensity (Martin-St Paul et al. 2013). As automated dendrometers capturing the seasonal trend of tree growth showed that drought onset, kept constant in TEE, was the main driver of inter-annual tree growth and not the -14% reduction in the carbon budget (Lempereur et al. 2015), we did not observe any change in tree growth despite reduced precipitation.

The second major impact observed in the TEE in the dry treatment was a +8% increase in tree mortality over time from the beginning of the experiment (figure 3). This was attributed to hydraulic failure after repeated prolonged droughts, and in accordance with the recent observed trend in the Mediterranean basin (Carnicer et al. 2011).

*Table 1*
*Functional responses of a Quercus ilex ecosystem to a 27% reduction in rainfall between 2003 and 2015*

| | | | |
|---|---|---|---|
| Tree mortality | ↗ | +8% | Unp. data |
| Tree growth | = | | Rodriguez-Calcerrada et al. 2011 |
| Leaf area | ↘ | -22% | Limousin et al. 2009 |
| Litter fall | ↘ | -21% | Limousin et al. 2009 |
| Acorn production | ↘ | -32% | Perez Ramos et al. 2010 |
| Transpiration | ↘ | -23% | Limousin et al. 2009 |
| Photosynthesis | ↘ | -14% | Misson et al. 2010 |
| Tree respiration | ↘ | -14% | Rodriguez-Calcerrada et al. 2011 |
| Soil respiration | ↘ | -11% | Misson et al. 2010 |

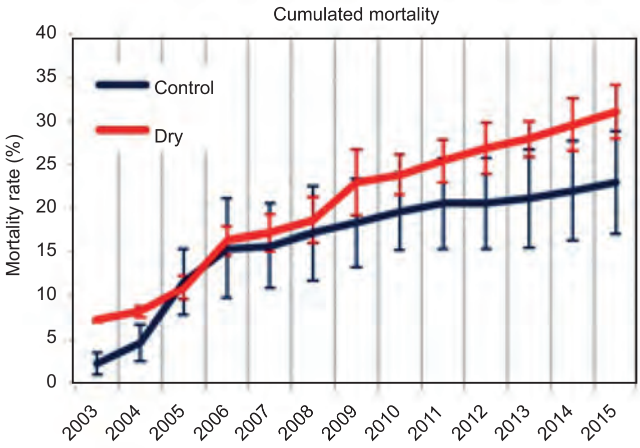


*Figure 3*
*Cumulated annual tree mortality (in %) in TEE under the control (dark blue) and dry (red) treatment since the beginning of the experiment in 2003.*

The increased mortality was not offset by enhanced regeneration, a key mechanism of forest resilience (Reyer et al. 2016b), as we observed a 32% decrease in acorn production (figure 4), and significant effects on seed maturation, seedling emergence and survival, and, to a lesser extent, on post-dispersal seed survival as a result of desiccation of winter acorns (Joet al. 2016).

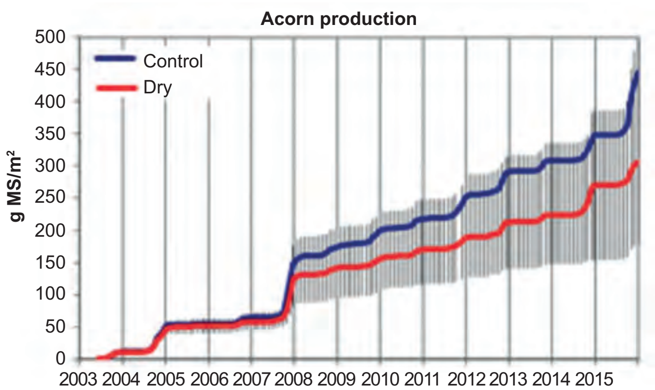


*Figure 4*
*Cumulated annual acorn production in TEE under the control (blue) and dry (red) treatments since the beginning of the experiment in 2003.*

Our study indicates rapid acclimation of the ecosystem to the reduced water supply, by saving carbon through a decrease in leaf and stem respiration, and saving water through a reduction in transpiring leaf area. This Mediterranean forest appears to be able to develop functional strategies to withstand increasing drought stress, but these strategies lead to tree self-thinning and increased tree mortality, together leading to forest opening and potentially toward open woodland or shrublands, two widely observed alternative systems in MTEs.

We compared the responses of leaf level physiological traits, branch level hydraulic traits, and stand level allocation traits to drought in the evergreen *Quercus ilex* in the TEE to a regional precipitation gradient (long term changes) with the driest extreme reaching the annual rainfall in TEE. At the leaf scale, gas exchange, mass per unit area and nitrogen concentration showed no response to drought as they did not change in either experiment (figure 6). A similar absence of response has been observed for xylem vulnerability to cavitation at the branch level (Martin St Paul et al. 2013). In contrast, the ratio of leaf area (LA) to sapwood area (SA) of young branches exhibited a transient response to drought because it decreased in TEE only in the four first years of treatment, but did not differ among the sites of the gradient. However, at the stand level, the leaf area index (LAI) decreased, and the ratios of stem sapwood area to LAI and of fine root area to LAI both increased in TEE and from the wettest to the driest site of the gradient. Taken together (figure 6) these results suggest a trajectory of tree acclimation to recurrent drought that shifts progressively from low (branch) to high (stand) organizational levels, and acts to maintain the leaf water potential within the range of xylem hydraulic function and leaf photosynthetic assimilation.

# Diversity of water use strategies in mixed Mediterranean shrublands enhance ecosystem resilience to variable drought features

The acclimation of perennial changes to changing precipitation regime is likely species-specific, so that additional studies using similar designs to the one we used at our *Quercus ilex* study site are needed in multispecies stands to better capture potentially contrasted strategies to cope with increasing drought. We therefore investigated how co-occurring Mediterranean species respond differently and compete under water limited conditions. From 2011 to 2013, we studied a typical *maquis* shrubland composed of *Arbutus unedo*, *Phyllirea latifolia*, *Cistus monspeliensis, Erica arborea*, *Pistacia lentiscus* and *Calicotome villosa* in northern Tunisia (36°36'18''N, 8°33'58''E), at the southern limit of the Mediterranean biome (see details in Longepierre et al. 2014). Interannual variability in species functioning and their response to increasing drought were assessed under a rainfall interception experiment. Weekly predawn plant water potentials were measured in the six species over the course of the experiment, along with plant moisture content, growth and leaf dynamic. We observed contrasted strategies among the species to cope with summer drought: deep rooted evergreen species (*Phyllirea latifolia, Pistacia lentiscus*) were able to maintain a water potential higher than -3MPa, while more shallow rooted species (*Erica arborea*) experienced severe water stress with water potential lower than -7MPa under the driest conditions (*Erica arborea*). Twig elongation was highly constrained in all the species below a water potential threshold of -1.2 MPa, but we identified different short term leaf area adjustment strategies, from fully evergreen for *P. lentiscus* and *P. latifolia*, to partially drought deciduous for *E. arborea* and summer deciduous for *C. villosa* as soon as water potential reached -1.2 MPa. We also observed that the species with the lowest predawn water potential (*E. arborea* and *C. villosa* ) started growth early so that twig elongation was not affected by the early drought in 2012, while in less water-constrained species (*P. lentiscus* and *P. latifolia*) twig elongation was seriously affected (figure 5). These results illustrate different strategies ranging from drought avoidance to drought tolerance, depending on root exploration, leaf life span and leaf phenology, indicating high ecosystem-level resilience independent of the particular drought feature occurring in a given year. They also extend our first result on the high resilience of MTEs to increasing drought. However, like in *Quercus ilex*, in most of these species, seed germination was shown to be affected by soil water deficit, but enhanced by fire cues, a peculiar feature of these highly flammable species (Chamorro et al. 2016).

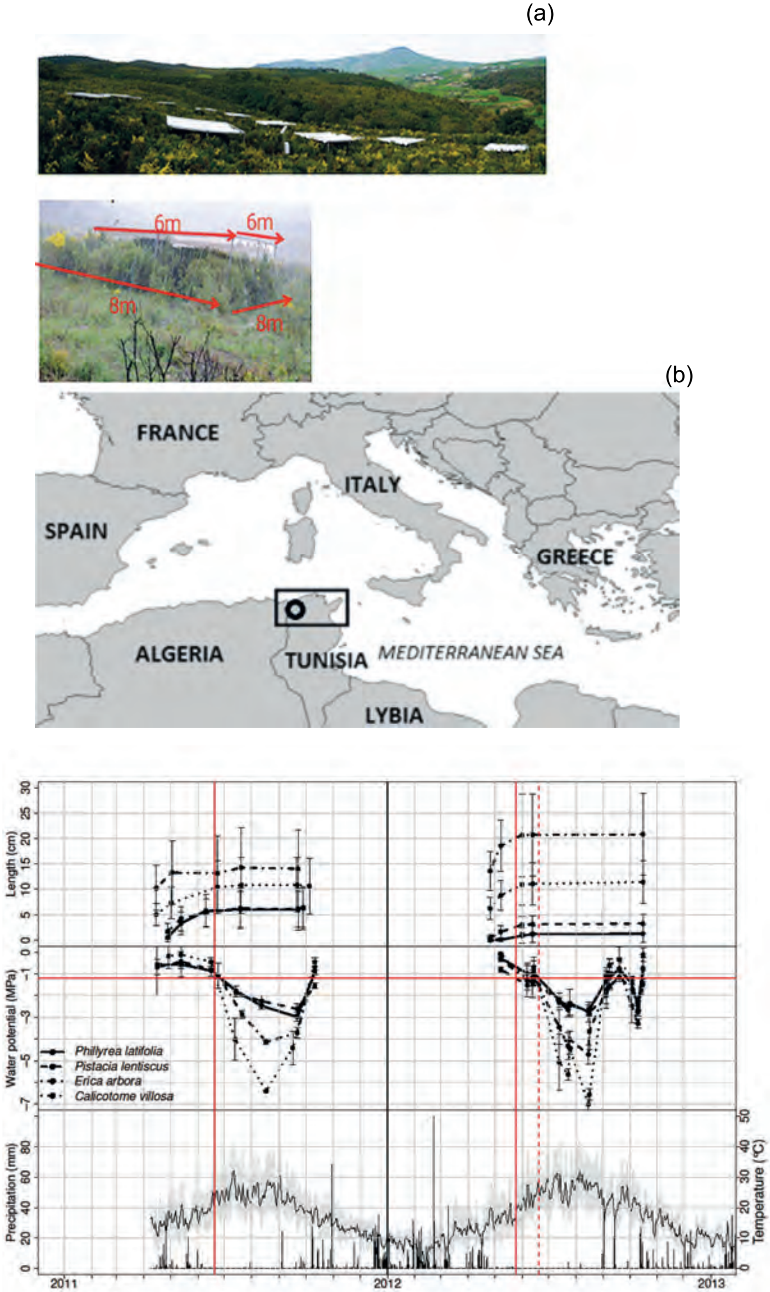


*Figure 5*

*Rainfall interception experiment in a mixed Mediterranean shrubland in Tunisia (a). Map showing the location of the experiment (b). The graphs show seasonal variations in temperature and rainfall in the period 2011-2012, predawn leaf water potentials (MPa) for* Phyllirea latifolia, Pistacia lentiscus, Erica arborea *and* Calicotome villosa, *and the yearly cumulated apical twig elongation in the same species (c). The horizontal red line represents the -1.2MPa threshold, and the vertical red line identifies the day of the year when this threshold was reached and twig elongation stopped.*

# Fire disturbances affecting MTEs: a process affected by climate change in a varying socio-economic context



From our experiments, we concluded that plant adjustments to drought lead to functional responses that affect the plant water budget and hence the leaf moisture content on one hand, and the biomass of leaves and twigs, two major components driving biomass combustibility, on the other hand. Adjusting leaf area to limit water loss and fine fuel would then decrease fire risk in the short term, so that the temporal trend of fire risk as a response to increasing drought is not the widely assumed linear trend (figure 6). The development of understory shrubs in tree gaps (Rodriguez-Calcerrada et al. 2013) and the dead plant material that accumulates as a result of increased tree mortality might actually contribute to a drastic increase in fire risk in the medium term. After the decomposition of wood necromass (a significant aspect of global biogeochemical cycles not covered in our experiment, but see Cornwell et al. 2009), fire risk would be driven either toward higher levels in the case of shrub encroachment, or to lower levels in the case of open shrublands, depending on drought intensity. Fire is actually the main disturbance affecting MTEs, and may abruptly affect the smooth trend in plant acclimation to increasing drought, and subsequently modify plant composition and ecosystem functioning in the long term.

Fires are to some extent controlled by human factors, both as a source of ignition and prevention and suppression. In southern France, despite the increase in drought intensity and in summer temperatures in recent decades (Ruffault et al. 2013), increasing expenditures for firefighting led to an abrupt decrease in burned area after the 1990s (figure 7), even during extreme years (2003, 2006) (Ruffault and Mouillot 2015). Figure 7 illustrates the differential relationship between annual burned area / summer drought index (SPEI3) for the pre- and post-fire suppression period, summer SPEI3 being the 3-month standard precipitation evaporation index for June-July-August obtained from the global gridded SPEI database (Begueria et al. 2010). Human factors are the most important drivers of global change in fire risk nowadays (see Turco et al. 2016 for a review of trends in recent burned areas in southern Europe), so that contrasted socio-economic status affecting expenditure for firefighting can significantly modify fire hazard and the subsequent ecosystem dynamics. Figure 7 also presents the temporal pattern in burned area in a contrasted socio-ecological system in Tunisia, where the ‘Arab spring’ revolution led to political instability, local riots and loss of government control over rural populations. We observed a 3-fold increase in burned area since 2011. The relationship between annual burned area and the summer SPEI3 drought index shows that 2011 and 2012 remain within the usual range of variability in burned area according to drought, only 2013 was out of the range of the historical record. This non-climatic trend can be attributed to social change, most of this additional burned area being related to military interventions in the southern pine forests (Chaambi national park), a key –but hardly predictable- aspect of ecosystems response to global and regional changes.

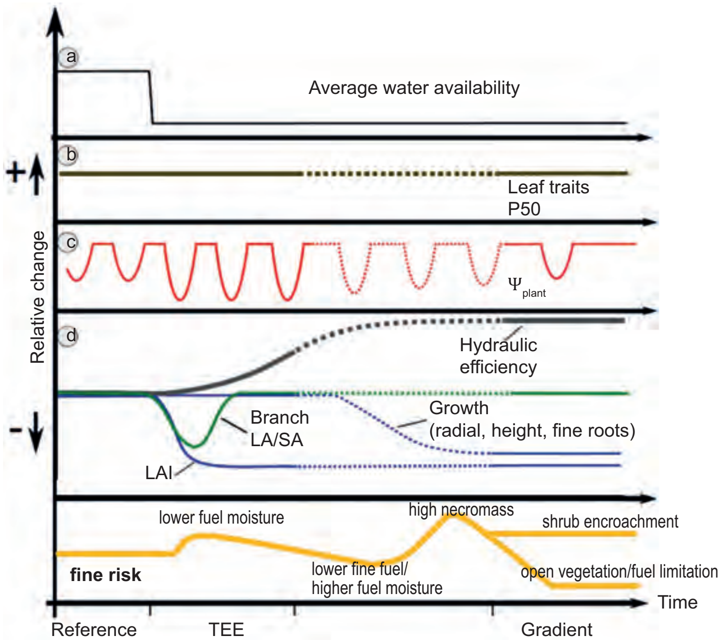


*Figure 6*
*Temporal dynamics of the responses of* Quercus ilex *to decreasing precipitation.*
*The y axis represents the relative changes from the reference value (intermediate site) when average water availability was reduced for a suite of traits. The x axis represents the time after the reduction of precipitation caused either by the TEE or the precipitation gradient. Panel (a) shows the level of water availability. Panel (b) shows changes in leaf traits and P50 (the water potential causing 50% loss of conductivity. Panel (c) shows the change in* $\Psi_{plant}$ *(plant water potential). Panel (d) shows the changes in shoot LA/SA (the ratio of apical shoot leaf area to sapwood area), LAI (the leaf area index); growth and hydraulic efficiency (i.e. the ability to transport and extract water). The dotted lines denote the interpolation between responses observed in the TEE and in the gradient. Implications for fire risk are shown as a combination of biomass moisture and changes in the amount of fine fuel.*

# Conclusion

Our combined multi temporal/multi scale approach including experimental throughfall interception and gradient analysis revealed the hierarchical adjustments of MTEs in the face of increasing drought, in the case of the evergreen *Quercus ilex,* leading to overall high resilience to this aspect of climate change. The multispecies approach in a *maquis* shrubland also revealed the multifaceted strategies a community exploits to withstand high variability (prolonged, earlier, later, more intense, bimodal) drought features. The latter experiment reinforced our results concerning the high resilience of MTEs with respect to diverse functional traits at the ecosystem level. In the future, it will be important to

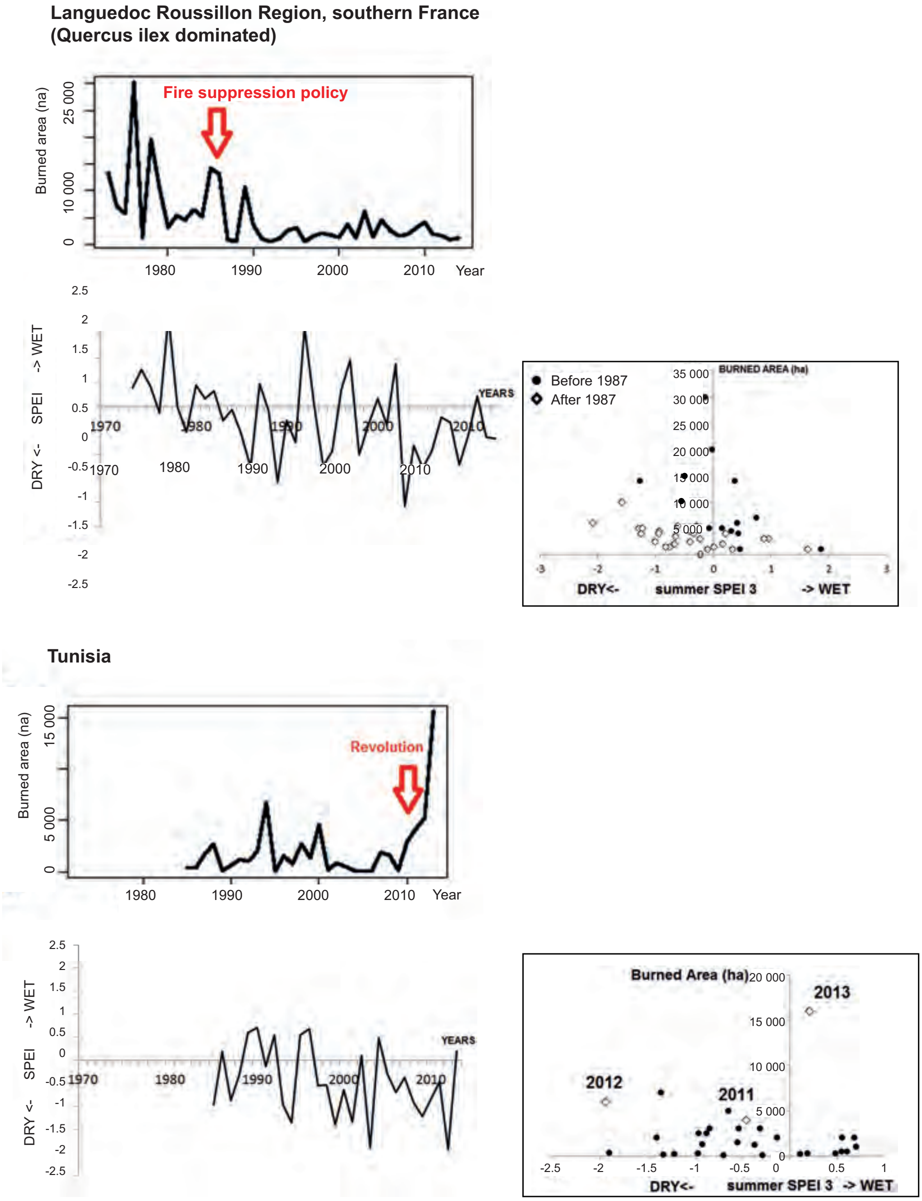


*Figure 7*

*Annual burnt area (in ha) in southern France (*Quercus ilex *dominated Languedoc Roussillon Region) (source www.promethee.com) and Tunisia (Source General Directorate for Forests, Direction générale des forêts Tunis, and Landsat images for the period 2000-2013) for the period 1973-2013. Red arrows identify the timing of abrupt socio-political changes such as the introduction of a new fire suppression policy in France in 1987 and the revolution in Tunisia in 2011. Temporal trends in the standard precipitation evaporation index SPEI and the relation between burned area and the summer SPEI3 are also shown for both sites.*

*Languedoc Roussillon Region, southern France (*Quercus ilex *dominated) Tunisia.*

assess the contribution of ecotypic differences in the acclimation processes, which could be achieved by incorporating common garden experiments in the design we used. However, fire disturbances remain a critical process, a partial understanding of which can be captured from vegetation functioning, but which are widely overlooked and difficult to predict when socio-economic and political issues are taken into consideration (Moritz et al. 2014).



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# Plant biodiversity and vegetation on Mediterranean islands in the face of global change

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## Introduction

The profound environmental heterogeneities and the complex historical biogeography explain the high diversity of landscapes and vegetation types in the Mediterranean Basin, one of the world's biodiversity hot-spots (Médail & Myers, 2004). The associated high levels of biodiversity and ecological complexity have favored the emergence of functional uniqueness in several ecosystems and plant communities that occur nowhere else. With about 10,000 islands and islets (approx. 250 inhabited by humans), the Mediterranean Sea can be considered as one of the largest archipelagos in the world. Its islands contain a significant component of Mediterranean biodiversity, notably a number of range-restricted species and peculiar vegetation types (e.g. Vogiatzakis et al. 2008; Médail, 2013, in press). The richness of Mediterranean insular nature is linked to the long-lasting influence of humans as 'designers' of landscapes, who have shaped vegetation dynamics through burning, cutting, grazing and plowing (Blondel, 2008). More recent threats linked to global environmental change (climatic and sea-level changes, biological invasions) weaken the biodiversity and functioning of these ecosystems.

# The diversity of Mediterranean islands

Mediterranean islands are a kaleidoscope of environmental and biotic conditions. This is due to the wide range of sizes (from the largest island of Sicily covering 25,700 km$^2$ to small islets a few dozen square meters in size), in altitude (from Mt. Etna, 3,342 m a.s.l. to flat islets only one meter a.s.l) and in remoteness, all of which represent key parameters in island biogeography. There are a total of 157 large islands exceeding 10 km$^2$ (1,000 ha) in size in the Mediterranean Sea, of which 86 (55%) are located in Greece (Médail, in press). Forty nine islands cover more than 100 km$^2$, of which 36 cover more than 200 km$^2$. Small islands (less than 10 km$^2$, www.initiative-pim.org) are the most common, and there are several thousand of such islands (Photos 1). Most islands belong to the Greek archipelago with *ca.* 7,600 islands and islets in the Aegean Sea, more than 90% of which cover less than 10 km$^2$ (Triantis & Mylonas, 2009). In the Ionian Sea, there are *ca.* 300 Greek islands and islets. Croatia is the second country in terms of the number of islands (n=1,246), including 79 islands covering more than 1 km$^2$ and 653 small islands and islets with vascular vegetation (Nikolić *et al.,* 2008).

*Photos 1*
*Example of small rocky islands.*
*Left: Capense island in N. Corsica (Cap Corse, Centuri), V.2015*
*Right: Es Vedrà island, a small (640 ha) island with an impressive peak (384 m) emerging from the sea SE of Ibiza island, IV.2014 (F. Médail).*

Nearly all Mediterranean island ecosystems are under the influence of the Mediterranean climate (Figure 1), except some parts of the high mountains of Corsica that contain subalpine and alpine vegetation belts with Euro-Siberian and even arctic-alpine plants. The insular vegetation types usually considered as 'typically Mediterranean' are the evergreen and sclerophyllous shrublands and forests under semi-arid bioclimatic conditions. Deciduous trees were widespread during the postglacial period, notably in the northern Mediterranean, but these forests were severely impacted by humans and their livestock.

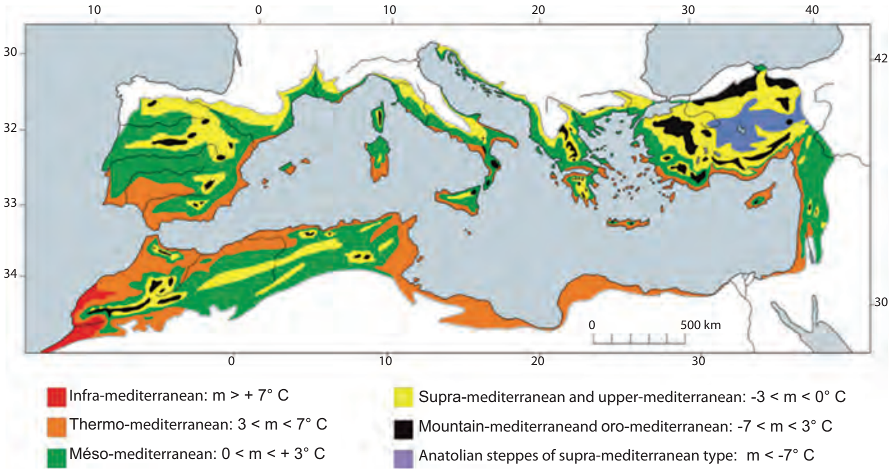


*Figure 1*
*Schematic distribution of major vegetation types in the Mediterranean region, according to phytoecological and bioclimatical criteria, notably the mean minimum temperatures of the coldest month (m) of the year (see Médail, 2008).*

The existence of endemic or range-limited plant species can determine specific patterns of vegetation types and landscapes. On large islands, plant endemism ranges from 8% to 17%, whereas the total number of taxa is greater than expected, usually between 1,600 and 2,800 species and subspecies (Table 1). In insular mountain ranges, the level of endemism is higher: above 1700 m a.s.l. endemics represent 35%-40% of the vascular flora in Corsica and in Crete. Each island has its own vegetation specificities even if major physiognomic structures may appear similar from one island to another. These include vegetation typical of low and medium altitudes, whereas the upper vegetation levels are restricted to the summits of the largest islands, notably Corsica, Sicily, Crete, Cyprus and Samos.

*Table 1*
*Indigenous plant richness and endemism level of the six largest Mediterranean islands (Médail unpublished data, various sources).*

| Island | Area ($km^2$) | Plant richness | Endemic richness | Endemism level | Endemic genera |
|---|---|---|---|---|---|
| **Sicily** | 25 426 | 2793 | 322 | 11.5% | *Petagnaea, Siculosciadium* |
| **Sardinia** | 24 090 | 2408 | 290 | 12.04% | *Castroviejoa, Morisia, Nananthea, Soleirolia* |
| **Cyprus** | 9 251 | 1633 | 142 | 8.7% | |
| **Corsica** | 8 679 | 2237 | 284 | 12.7% | *Castroviejoa, Morisia, Nananthea, Soleirolia* |
| **Crete** | 8 261 | 2240 | 395 | 17.6% | *Horstrissea, Petromarula* |
| **Balearic islands** | 4 987 | 1551 | 140 | 9% | Only on eastern islands: *Femeniasia, Naufraga, Soleirolia* |

# Insular plant biodiversity facing current global environmental change



The Mediterranean climate, in particular the drastic und sometimes unpredictable nature of climatic patterns and resource availability, puts severe and contrasted stress on species and communities. The impacts of climate change in the 20th century are less well documented than direct human impacts, but the situation is now changing rapidly and severe impacts on island ecosystems and biodiversity are expected.

## Widespread human impacts and land use changes

Most changes in Mediterranean ecosystems are linked with human land use and its dynamics over time and these will likely continue to play a major role (Blondel & Médail, 2009). Beginning in the 19th century and with a constant acceleration throughout the 20th century, major land-use changes on large and medium islands were characterized by the widespread collapse of the 'traditional Mediterranean tryptic' *ager-saltus-sylva* (agriculture, pastoralism, forestry) that shaped insular landscapes for millennia. Until the middle of the 20th century, natural resources were crucial for island populations, notably for food, livestock, nutraceutical and healing compounds. For example, in a single year (1867) more than 7,000 metric tonnes of wood and coal were consumed in Palma de Mallorca for domestic and artisanal uses (Mayol, 1995). The end of subsistence economies on most islands led to reduced pressures on natural resources and therefore a general increase in matorral and forest areas, as well as to the abandonment of cultivated terraces that were formerly the rivet of agricultural landscapes on steep and mountainous islands (e.g. Cerabolini *et al.*, 1996, for Elba; Petanidou et al. 2008, for Nisyros).

These trends cannot be generalized to all islands. For example, the relation between successional processes and increased grazing pressure after land abandonment is still uncertain in many Mediterranean islands (e.g. Rühl & Pasta, 2008; Schaich et al. 2015). In some cases, the end of traditional agricultural activities has led to severe soil erosion or to the rapid extinction of many ruderal endemics and several particular archaeophytes. Throughout the Aegean archipelago, the collapse of cultivation practices on terraces in the early 20th century led to major landscape changes, and has resulted in the near disappearance of traditional crops since the 1960s: lentils on Samos and Lesvos, wheat on Chios, beans on the Cyclades. The unique terraced landscapes have disappeared on most of these islands. In western Crete, human emigration from the arid mountains reduced agricultural land area by almost 40% between 1945 and 1990, thereby favoring the recovery of forest ecosystems dominated by the coniferous *Cupressus sempervirens* and *Pinus brutia.* The same process has taken place on the Balearic islands, for example in Mallorca, where the extent of Aleppo pine forests has multiplied more than fivefold in the last century (Marull et al. 2015). Similarly, holm oak forests have increased from 5,000 ha to more than 10,000 ha in Mallorca, and from 900 ha to 2,600 ha in Menorca since 1860 (Mayol, 1995). In contrast, the tall shrublands and natural forests of eastern Sardinia decreased by 35% between 1955 and 1996, whereas pastures, burned low shrublands and afforestation are progressing. Landscape dynamics are more contrasted in Corsica. Since the beginning of the 20th century, land abandonment has led to an increase in shrublands and forested areas. Forest cover, which was only 17.6% in 1866 (153,775 ha), is currently 58%, an increase of 3.3% over a period of 150 years (Panaïotis et al. 2015). This increase can be locally counterbalanced by frequent fires, often linked to illegal pastoral practices. Rural areas in Corsica still account for 80% of the land and traditional summer transhumance herds use more 130,000 ha throughout the mountain range (source: *Parc Naturel Régional de Corse,* PNRC). Grazing is an obstacle to forest expansion and regeneration, it has been practiced on Mediterranean islands for millennia, shaping both landscapes and their biodiversity. Grazing is intensive on most Greek islands. Uncontrolled practices can lead to overgrazing and even to land degradation under arid and semi-arid climates (e.g. Papanastasis et al. 2002).

Today, there is a slight increase in permanent human population on the bigger islands, whereas the medium-sized islands – except some hot-spots of tourism such as Corfu and Djerba – are undergoing a population decline. Even on large islands, disparities are strong between densely populated islands like Malta (1,330 people/km$^2$) and less-populated ones like Corsica (36 people/km$^2$). Since the 1960s, island tourism has increased everywhere, with a paroxysm on two Balearic Islands (Mallorca and Ibiza) where a peak was reached in 2000-2001 with 11 million tourists. This pressure has led to major urban development along the coasts, threatening fragile ecosystems such as sand dunes, wetlands and, to a lesser extent, rocky habitats. For example, on the Greek island of Skiathos (N. Sporades), the development of tourism since the 1970s has led to an 80% reduction in these coastal ecosystems (Economidou, 1995).

## Impacts of climatic change

With an expected temperature increase of 3 ° to 5 °C in the Mediterranean over 21st century, potential evapotranspiration is expected to reach an average of 200 mm annually, which is equivalent to a loss of 50 mm in annual rainfall (Le Houérou, 1990). The expected shifts in vegetation belts resulting from increased aridity and a 3 °C increase in temperature will be an upward shift of approx. 545 m (almost the amplitude of a vegetation belt) and a 50–80 km northwards shift in latitude (Médail & Quézel, 2003). These impacts will be exacerbated on islands where no (or insufficient) areas are available for such shifts. The flora and vegetation of the alpine areas (i.e. mostly the oro- and alti-Mediterranean belts) and the spatially restricted summit areas of mountain ranges will probably be the most threatened, as in the Lefka Ori massif in Crete (Kazakis *et al.,* 2007). In Corsica, this is particularly the case of arctic-alpine species (*ca.* 25 taxa) in the alpine vegetation belt (Contandriopoulos & Gamisans, 1974).

It is too simplistic to consider a single range shift of plant communities in response to global warming. As suggested for Mediterranean mammals, the effects of climate change on species distribution and communities may consist of changes in community structure (Maiorano *et al.,* 2011). The extent to which many organisms will be able to cope with climate change is still largely an open question, especially because climate change is now taking place at an unprecedented rate. Microevolutionary changes may occur rapidly in fitness related traits such as the flowering time in plants (Peñuelas *et al.,* 2002). Differential responses of organisms interacting in complex food chains or symbiotic associations may also disrupt interactions that are essential for ecosystem functioning such as pollination or seed dispersal.

Climatic change is also a threat for insular plant populations and communities linked to wet habitats or mesophilous conditions, including some endemics that constitute the cornerstone of Mediterranean plant diversity. This is the case of two endemic species of the Apiaceae family restricted to the Balearic Islands. *Apium bermejoi*, a narrow endemic of Menorca located in a single area of 50 $m^2$ where the *ca.* 100 individuals occupy only one square meter. As this critically endangered plant is vulnerable to prolonged droughts, its present decline is probably related in part to a series of dry summers (Moragues & Mayol, 2013). The narrow ecological niche of the palaeoendemic *Naufraga balearica,* only distributed along a short section (*ca.* 15 km) of the north facing slopes of the northern Majorcan coast (Figure 2), explains its current extreme rarity (Fernández-Mazuecos et al. 2014) - rapid climatic shifts could jeopardize its survival. In Cyprus, several populations of narrow endemics (*Onosma caespitosa, Salvia veneris, Sideritis cypria*) are also threatened by rainfall reduced by 20% to 40%, and warming, both of which could modify their germination window in the fall (Kadis & Georghiou, 2010).

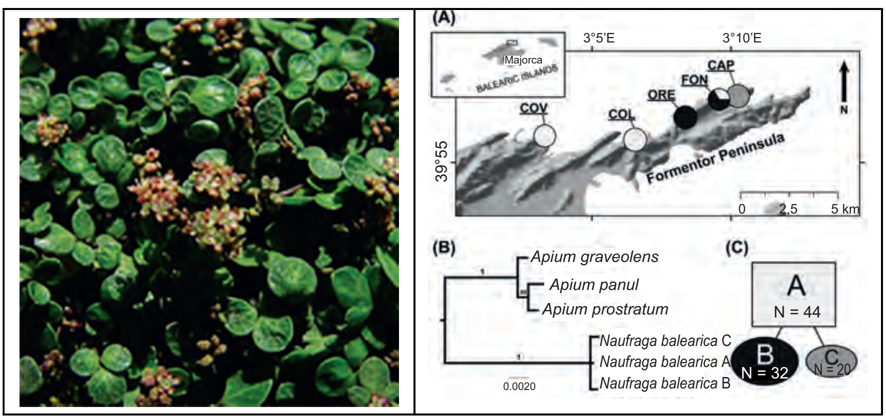


*Figure 2*
*The highly threatened narrow endemic* Naufraga balearica *(Apiaceae) located in the north-western part of the island of Majorca, with the distribution of the three haplotypes across the five sampled populations (a), the phylogenetic consensus tree (b) and the statistical parsimony network (c) of plastid DNA haplotypes showing the ancestral haplotype A (Fernández-Mazuecos et al. 2014).*

So far, there is only little robust evidence for direct depletion or extinction of populations due to climate change. About 10 endemic species are known to have become extinct on the Mediterranean islands, of the *ca*. 40 Mediterranean plants presumed to be totally extinct in this region (Blondel & Médail, 2009). Recent studies focused on the Cretan endemic tree *Zelkova abelicea* (Fazan et al. in prep.), and on some plant communities (e.g. Henne et al. 2015), showed that the ecological amplitude of many so-called 'temperate' species that thrive on Mediterranean mountains may have been underestimated. Local persistence of Mediterranean plants, notably perennials, in diverse microhabitats may be due to multiple demographic strategies of persistence by longevity or regeneration, depending on the local or regional conditions (García & Zamora, 2003). This is corroborated by the important role played by glacial refugia on islands (Médail & Diadema, 2009). However, most plants interact with bioclimatic characteristics at a physiological rather than macro-climatic level (Curtis et al. 2016). Differences in small-scale habitats in a landscape may therefore explain species' ability to cope with drastic and changing climate. The high habitat heterogeneity of Mediterranean-type ecosystems may thus represent an 'ecological insurance' for the future persistence of plant species at local scale, allowing species to migrate locally in more favorable ecological niches. Nevertheless, at the scale of small islands, this may not be sufficient to ensure the survival of highly specialized plants. The future persistence of 'islet specialists' such as the small annual *Nananthea perpusilla* (Asteraceae) in some shady and humid patches of islets around Corsica and Sardinia may well be at risk (photos 2).

*Photos 2*
*The large granite rocks on some small islands surrounding Corsica and Sardinia form a highly specialized ecological niche hosting the palaeoendemic Asteraceae* Nananthea perpusilla *in temporary humid and granitic soils with shaded exposure;*
*Cavallo island (Lavezzi archipelago, S. Corsica) III.2014 (F. Médail).*

## Impact of sea level rise

Sea level rise (SLR) is another important component of climate change. At the end of the last glacial period, a major consequence of climatic oscillation from cold to warm conditions was the melt of the Northern Hemisphere ice sheets causing a continuous eustatic sea level rise worldwide. In the Mediterranean

Sea, the main part of this marine transgression occurred before *ca.* 60,00 cal. yr B.P, with major disparities between areas. Some intra-island phylogeographies – such as for the narrow Balearic endemic *Senecio rodriguezii* (Molins *et al.,* 2009) – indicate an "island beneath island syndrome", i.e. a split of populations into several isolated and genetically divergent lineages that are explained by the repeated cycles of sea level changes during the Quaternary.

A rapid rise in global sea levels is expected in the coming decades. Regional rates of sea level change may increase by a factor of 1 to 6 relative to the observed long term rates (Galassi & Spada, 2014). Coastal ecosystems and small islands are especially threatened. Effects include the exacerbation of coastal erosion, the submersion of low elevation islands and flat coasts, and the salinization of coastal wetlands (Nicholls et al. 2016). Island biodiversity generally depends not only on immigration-extinction dynamics, but also on changes in insular area, isolation and connectivity (Weigelt et al. 2016). On a small Mediterranean island (Cavallo, S. Corsica) Holocene sea level changes played a significant role in loss of wetland biodiversity and ecosystem changes because of the increase in salinity caused by marine intrusions (Poher et al. submitted). Analysis of coleopteran fossils preserved in a 7,000 year sedimentary record showed that 60% of past wetland beetle fauna became locally extinct as a result of regime shift in this freshwater pond. The largest impoverishment occurred 3,700 years ago when the relative Mediterranean sea- level rose more than –1.5±0.3 m.

The Gulf of Gabes, in south-eastern Tunisia, is one of the Mediterranean areas that is most threatened by sea level rise, estimated locally at 5.7 mm per year. Geo-archaeological studies mention significant flooding of coastal lands and antique remains, up to two meters 2,000 years ago (Slim et al. 2004). This had profound impacts on the biodiversity of the flat and erodible islands of Djerba, Kneiss and Kerkennah (Médail *et al.,* 2015) (Photos 3). On the latter, land salinization has led to a sharp increase in *sebkhas* (+ 20% between 1984 and 2011) and a 27% decline in palm groves, equivalent to 26 $km^2$ (Etienne *et al.,* 2012).

*Photos 3*
*Typical vegetation of the large satellite islands of the Kerkennah archipelago (E. Tunisia).*
*Left: open steppe with* Lygeum spartum *(Poaceae);*
*Right: halophilous shruby vegetation on sebkhras with* Arthrocnemum macrostachyum *and* Sarcocornia fruticosa *(Amaranthaceae) (F. Médail).*

The effects of SLR might be less harmful for plant biodiversity on rocky island or coasts, because a slight altitudinal rise of halophilous communities and species towards the salt-tolerant habitats present just above could take place. Nevertheless, this shift may be limited by disturbed habitats on land. In "pocket beaches" in Provence (France), Brunel and Sabatier (2007) found an 12.1 ± 3.5 m retreat in the shoreline between 1896 and 1998, of which 5.8 ± 3.5 m was caused by SLR. On small islands like Porquerolles (Port-Cros National Park) pocket beaches could almost completely disappear (from 75% to 97% regression of their present surface area) by 2100. Because of frequent coastal cliffs or rocky slopes blocking landward migration, typical plant communities and species of fixed maritime sands (e.g. the psammophytes *Eryngium maritimum, Otanthus maritimus, Pancratium maritimum* of the grey dunes) could become locally extinct on various islands.

## Increasing forest fires

Like grazing, forest fire has been a major driving force of Mediterranean ecosystem dynamics since the emergence of the Mediterranean climate, 3.2 Ma ago. For the emblematic Corsican pine (*Pinus nigra* subsp. *laricio*), fires have played a key role in the functioning of these mountainous woodlands since this tree has survived mean fire-return intervals of 80 years over the last 13,200 years (Leys et al. 2014). Fires contributed to the frequent dominance of shrubland on islands during the mid-Holocene (*ca.* 8,000–7,000 cal. years BP) under dry conditions, as is the case of the *Pistacia* matorrals in Sicily and Malta (Djamali et al. 2013), and the dense *Erica scoparia* and *E. arborea* stands in north-eastern Sardinia (Beffa et al. 2016).

Fires can slow down the expansion of forest cover explained by the general collapse of traditional human practices on islands, in particular on persisting terraces that promote fast vegetation recovery. Thus, mature stages of woodlands are scarce because of recurrent fires, and matorral, and sometimes xerophytic grasslands, still often dominate insular landscapes. In Greece, the situation has been of particular concern for the last few decades given the increase in frequent intense wildfires. On Thasos Island, for example, a series of wildfires since 1984 has reduced forest cover from 61.6% to almost 20% (Ranis *et al.,* 2015). Furthermore, there often is spatial congruence between the most fire-affected micro-regions and the main cattle-rearing regions, like in Corsica. On this fire-prone island, 28,000 starting fires occurred between 1973-2004 (i.e. ≈ 1000 starting fires /year) and a third of the total surface area of Corsica was burned in a period of 30 years.

Fire regime changes and the occurrence of extreme fire events (or "megafires") are related to both land use change and climate change, and involve multiple biotic and socio-economic drivers (e.g. Pausas & Keeley, 2014). It is difficult to disentangle their relative importance because the management of Mediterranean landscapes plays a major role. In the western Mediterranean basin, a fire regime shift has occurred and fires are now less fuel limited and more drought-driven than before the 1970s (Pausas & Fernández-Muñoz, 2012). In the future, increased drought could increase fire activity on most Mediterranean islands, with secondary effects of land degradation and erosion.

The need to combine a multi-factorial approach is illustrated by the case of *Abies cephalonica* on the Greek island of Kefalonia (Politi *et al.,* 2011). The decrease of these fir populations has been attributed to different causes such as root damage, infestation by mistletoe, pathogens or insects, and more intense and more frequent extreme drought events probably in relation with the climatic warming trend,. Extreme drought events contribute to the recent increase in fire episodes spreading at high altitudes and are threatening non-fire resilient species whose future persistence is jeopardized in such insular situations.



# Conclusion

Phylogenetical and phylogeographical studies have demonstrated the complex historical biogeography of the Mediterranean Basin and also the importance of islands as reservoirs of unique genetic lineages, notably for most endemics and narrowly distributed plants (Médail & Diadema, 2009). Nevertheless, the time frame and evolutionary consequences of biogeographical events linked to repeated cycles of island connections and isolation, in relation to marine regressions-transgressions, remain largely unknown (Mansion *et al.,* 2008). This is of particularly concern for efficient evolutionary conservation of these heterogeneous insular floras.

With the biome crisis of the Mediterranean basin (Hoekstra et al. 2005), islands constitute key ecological systems to ensure the preservation of coastal plant biodiversity. And while insular systems still represent fascinating ecological systems, they are also key entities to disentangle the role of environmental versus human pressures in the long-term preservation of these biodiversity hot-spots. Because of increased threats across the Mediterranean region and the complex consequences of climate change (Klausmeyer & Shaw, 2009), it is crucial to observe, monitor, and analyze changes in vegetation and plant biodiversity across ecological and biogeographical gradients. Mediterranean islands, notably the small ones, are favorable sites for such long-term observations as well as for monitoring at various spatial scales. These “natural insular microcosms” are indeed appropriate systems to study adaptation to climate change by species or communities, and the functional biogeography approach (Violle et al. 2014) is undoubtedly an interesting topic that needs further research.

The diversity of situations facing Mediterranean islands should facilitate their integration as laboratories or testing grounds of extinction in relation to global change and human pressures. To this end, it would be useful to combine reactive approaches on the most threatened (often largest) islands, and proactive approaches on relatively less threatened islands (notably small islands and islets). Multi-disciplinary collaboration among prehistorians, archaeologists, palaeoecologists, historians, socio-economists, soil scientists, ecologists and biogeographers is needed to disentangle the complex interactions between past human societies and insular environments. Enhancing these interdisciplinary research efforts is a prerequisite for the design of sound policies and practices concerning the conservation of these unique and fragile insular floras and plant communities (Médail, 2013). The smallest islands should not be neglected, as they are often isolated territories where micro-speciation processes occurs, offering modern refuge-areas for diversity that is put at risk by the impacts of human activity on the coasts of the adjacent mainland.

Owing to their high biotic originality and vulnerability to global change, Mediterranean islands and islets urgently require integrated and ambitious conservation planning aimed at the long-term preservation of their outstanding biodiversity and cultural heritage.

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# Using the past to predict the future

## The case of French Mediterranean orchids

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## The time has come to document patterns of biodiversity variation in the Mediterranean

A major issue in ecology is understanding the drivers of temporal changes in the spatial distribution patterns of species. Species are distributed in space in response to a restricted range of compatible conditions defined by their ecological niche (Chase and Leibold, 2003), but also in response to long-term environmental changes (Blondel et al. 2010). Given the currently accelerating global environmental change, we need to understand and predict the influence of ongoing global changes on biodiversity to rank priorities for conservation planning (Margules and Pressey, 2000; Bottrill et al. 2008). Several studies have pinpointed the effect of global changes on biodiversity showing latitudinal/altitudinal displacements, reductions in species ranges and local or global extinctions (Hughes et al., 2000; Parmesan and Yohe, 2003; Vogt-Schilb et al. 2015; 2016; Bose et al. 2016). Measuring the amplitude, and understanding the mechanisms underlying biodiversity shifts in space and over time has become a central issue in conservation biology. Species will be impacted differently across their distribution range, with the biggest changes in areas prone to the greatest environmental shifts (e.g. climate, land use; Underwood et al. 2009). For this reason, one can predict that species with a narrow niche, a localized distribution area and/or low dispersal ability will be more impacted by environmental shifts and less prone to respond (Thuiller et al. 2005; Devictor et al. 2008; Zhu et al. 2012).

The nature and amplitude of past and current environmental changes vary considerably depending on the regions concerned, their historical legacies, and their environmental characteristics (Walther et al. 2002; Reidsma et al. 2006; Hansen et al. 2015). Like species, regions differ in their vulnerability to environmental changes. Therefore, geographical concentrations of biodiversity are also often hot-spots of threats to biodiversity (Myers et al., 2000). Such areas include the western part of the Mediterranean basin, where current landscape dynamics are greatly affecting biodiversity patterns, notably as a consequence of the marked decline of agro-pastoral practices and encroachment since the Second World War (Underwood et al. 2009; Blondel et al. 2010; Sirami et al. 2010). This region now faces major climate change including increasingly frequent dry periods (Schleussner et al. 2016). Observations at large geographical scales are needed to investigate the current dynamics of species distribution in the face of global environmental change. Data on several regions/countries should cover broad environmental gradients in order to address species' responses under different regimes of environmental change (Pearson and Dawson, 2003). To date, studies of changes in distribution in vulnerable ecosystems at large spatial scales are rare (Settele et al. 2014).

## The time has come to develop methods for the quantification of biodiversity changes

Measuring shifts in biodiversity patterns requires appropriate and specific methods (Vogt-Schilb et al. 2016). The satisfactory quality and quantity of information (species identification, accurate localization, period of observation, etc.) are primary prerequisites. Unfortunately, most historical data do not satisfy these requirements, for instance because observers had a wide variety of motives, including naturalism, and only paid attention to the quality of the records. Diachronic analyses are appropriate ways to explore variations in biodiversity over time. The main methodological requirement is using identical methods (sampling design, timing and locations) to allow comparisons between past and present data (Kéry et al. 2006; Vogt-Schilb et al. 2016). In other words, the format (in terms of method, choice of sites, period of visits, and recorded species) used for the collection of past data will determine the research conducted in the present.

Once the past and present data have been acquired, the next methodological challenge is to establish inter-annual variations in the presence of species in the past and in the present and to distinguish them from the true variation in species presence between the two periods of observation in order to determine biodiversity loss or gain. For instance, inter-annual variations in species presence, as well notable differences in detectability among species (Kéry et al. 2006; Archaux et al. 2009; MacKenzie et al. 2009; Vogt et al. 2013; Iknayan et al. 2014) have to be taken into account by sampling in several consecutive years. A second challenge in ecology is designing adequate statistical procedures to assess the diversity of ecological drivers of species' distributions from local to regional scale and to predict their response to environmental changes (Thuiller et al. 2008; Munoz, 2010). In other words, it is essential to design statistical tests that acknowledge the structure of regional species pools case by case (Lessard et al. 2012), depending on their different functional (de Bello et al. 2012) and biogeographical properties (Carstensen et al. 2013).

## Orchids as an ecological model to evaluate biodiversity shifts

Here, we investigate the temporal shifts in the distribution patterns of orchids in contrasted environmental contexts (continental France vs. Corsica) in the Mediterranean region. Orchids are a particularly relevant group for documenting changes in the presence and distribution of species, for the three following reasons. First, orchids are a species rich and ecologically diversified group, particularly in the Mediterranean region (Schatz et al. 2014); some species are widely distributed, whereas others are more or less narrowly endemic (Bournerias and Prat, 2005). Second, orchid niches are segregated over broad abiotic environmental gradients (continental, oceanic and Mediterranean climatic regions, Munoz, 2010) in Europe. Third, orchids are particularly vulnerable to changes in climate and land cover (Wotavova et al. 2004; Pfeifer et al. 2006) due to their dependence on both pollinators and fungal symbionts (Selosse et al. 2006). In the last decade, the decline of many orchid species has been reported in Europe (Jacquemyn et al.

2005; Kull and Hutchings, 2006; Schatz et al. 2014), as well as in Australia and North America (Whigham and Willems, 2003; Duncan et al. 2011) but, surprisingly, no trend has been reported for the orchid rich Mediterranean region. To record orchid occurrence, a single visit by the observer is generally not sufficient to identify all species present at one site. In the Mediterranean region, an average of around 80% of orchid species are detected during a single visit (Vogt-Schilb et al. 2013). Three sampling years are necessary to provide an exhaustive view of the community, including rare or inconspicuous species or barely visible (detectable) ones (Kéry et al. 2006; Vogt-Schilb et al. 2013).

We recently conducted two studies on the diachronic variations of orchids in Mediterranean France, and designed and applied an appropriate method to compare changes in the composition of communities. In the first analysis, we characterized the recent dynamics of orchid distribution in Western Europe, with regards to climate and land cover changes but also the habitat requirements of species (Vogt-Schilb et al. 2015). We used surveys made by the French Orchid Society on 134 orchid species in France, Belgium and Luxembourg over a 20 year period (1985-2005) (Vogt-Schilb et al. 2015). In the context of a large-scale biogeographical and ecological gradient of orchid richness from the Mediterranean to Northern temperate areas (Schatz et al. 2014), we expected that the significance of extinction or colonization patterns would depend on the number of species likely to be locally present. In order to identify the significance of recorded changes (disappearance/appearance) within each administrative unit and for each orchid species, we applied a statistical procedure (called 'null models') that acknowledges variations in orchid richness in space and the overall distribution of orchid species.

We found sharp declines in most orchids in northern France, Belgium and Luxembourg, and many new appearances in the Mediterranean region (Figure 1). We found more declining species among heliophilous (shade-intolerant) orchids than among sciaphilous (shade-requiring) ones. This is due to the loss of open natural habitat in the highly urbanized regions in the northern part of the study area. No significant differences in appearance or disappearance were detected between Mediterranean and Euro-Siberian species. Changes in land cover were found to be the primary driver of orchid distribution dynamics, with a significant role of urbanization (Duncan et al. 2011), reduction in open habitats (Sirami et al. 2010) and the destruction of wetlands (Hartig et al. 1997). Concerning the link between conservation policies and orchid dynamics, our study revealed a major decline in species of orchids in metropolitan France considered as threatened by IUCN et al. (2010) and those that are nationally protected (Bournérias & Prat, 2005). This suggests an urgent need for complementary conservation measures and updated tools (Schatz et al. 2014). When considering the contrasted decline between the northern and southern parts of the study area, one may argue that the ongoing change will exacerbate the existing unbalanced geography of species richness, and that the high number of species in the Mediterranean is well conserved. The historical dataset analyzed here was provided by a network of amateur naturalists (3,000 observers belonging to the French Orchid Society) who fruitfully collaborated with researchers and enabled updating of the recent changes in orchid distributions and their drivers (Schatz et al. 2014; Vogt-Schilb et al. 2015).

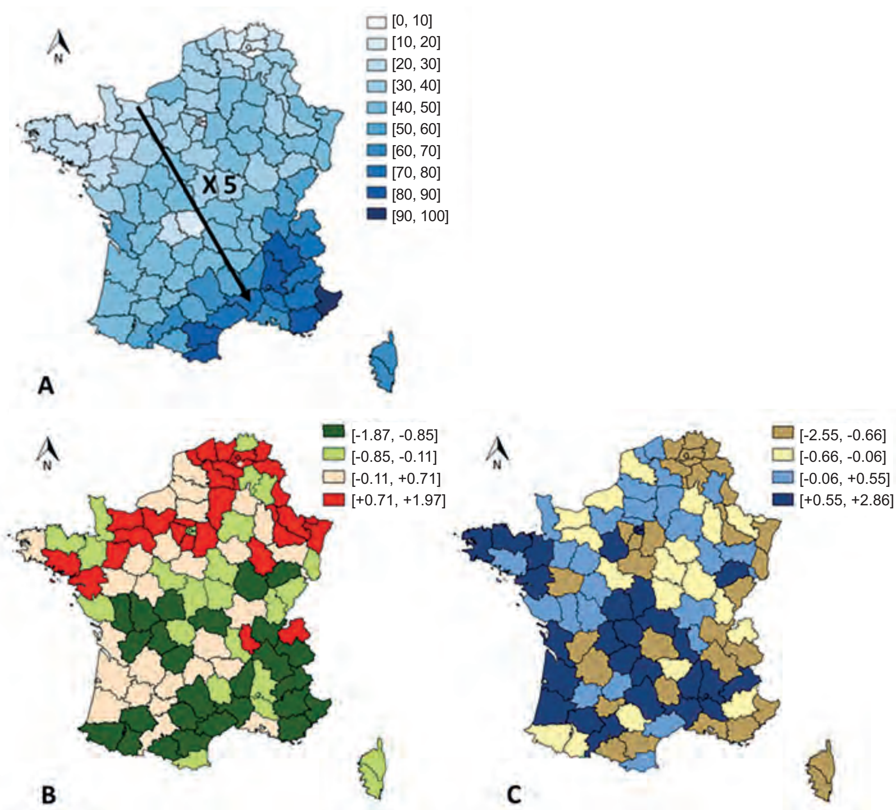


*Figure 1*
*Number of orchid species (A) and patterns of orchid disappearance (B) and appearance (C) across administrative units in France, Belgium and Luxembourg. In (B) and (C), a positive value indicates that there were more changes than would be expected by chance, while a negative value indicates that there were fewer changes than would be expected by chance.*
*From Vogt et al. 2015.*

In the second analysis, we evaluated the effect of an increase in forest cover on the local dynamics of orchids using data from two field surveys conducted 27 years apart (1982-1984 vs. 2009-2011) at a set of 45 sites in Corsica (Vogt-Schilb et al. 2016). This effect has already been investigated in northern Europe (Jacquemyn et al., 2005; Kull and Hutchings, 2006), but never in the Mediterranean region. We applied a Bayesian multispecies site-occupancy model to each of the 36 orchid species recorded at these sites to estimate their probability of detection. The analysis showed that the probability of detection of orchids is significantly and positively correlated with the density of their population and the size (height) of their individuals (Vogt-Schilb et al. 2016). We then took species related under detection biases into account in estimating their temporal dynamics. The woody plant cover in the study area increased from 43.3 ± 3.5% to 61.2 ± 3.4% (+18% on average). During the same period, orchid communities underwent a marked changed in composition at the local scale (Fig. 2), with no effect on species richness at the regional scale (Vogt-Schilb et al. 2016). However, the abundance of heliophilous species decreased more sharply than that of sciaphilous species. As a result, conserving landscape mosaics could increase species richness at the local scale by providing a wide range of suitable habitats for orchids of different ecologies and limit species turnover (Vogt-Schilb et al. 2016). However, similar observations conducted in two continental and Mediterranean French regions, where the observed increase in woody plant cover was at least twice as high (more than 30%) during the same period (see also Debussche et al. 1999; Sirami et al. 2010; Titeux et al. 2016), revealed a marked decline in the abundance of orchid species at both local and regional scale (Schatz et al. in prep).

In summary, the first study in three different countries revealed a good conservation status of orchids in the Mediterranean region in terms of species appearances or disappearances across administrative units (Vogt-Schilb et al. 2015). Conversely, studies in three Mediterranean regions revealed detailed variations in the conservation status, including a high turnover of orchids in Corsica but a decline in species in the continental regions due to a bigger increase in woody plant cover. Recent urbanization and variations in woody plant cover are thus two important drivers of rapid reduction in the presence of orchids, beyond the effects of the ongoing climate change.

## Outlook for the investigation of biodiversity changes in a context of global change

Similar data concerning diachronic variations are available for other taxonomic groups, including butterflies (Ekross et al. 2010), birds (Devictor et al. 2008; LeViol et al. 2012) and fungi (Gange et al. 2007; Kauserud et al. 2008). The diversity of responses in each of them (a northward shift or a shift in altitude for the two first and a shift in their phenology in fungi) and the variability of species-specific response within each taxonomic group underline the complexity of the impacts of global changes. Observations from the past are important for the reconstruction of earlier conditions, and they offer unique opportunities to assess the ecological plasticity of species assemblages. In this context, historical records belonging to naturalists, museum and herbaria collections are extremely valuable for scientific studies of changes in biodiversity (Lavoie, 2013; Vogt-Schilb et al. 2016). Beyond the diachronic variation in species presence and distribution, we also need to recognize interactions with other organisms that determine survival and reproduction. In Great Britain and the Netherlands, wild bees and hoverflies have declined in parallel with insect-pollinated plants, whereas wind-pollinated plants have increased (Biesmeijer

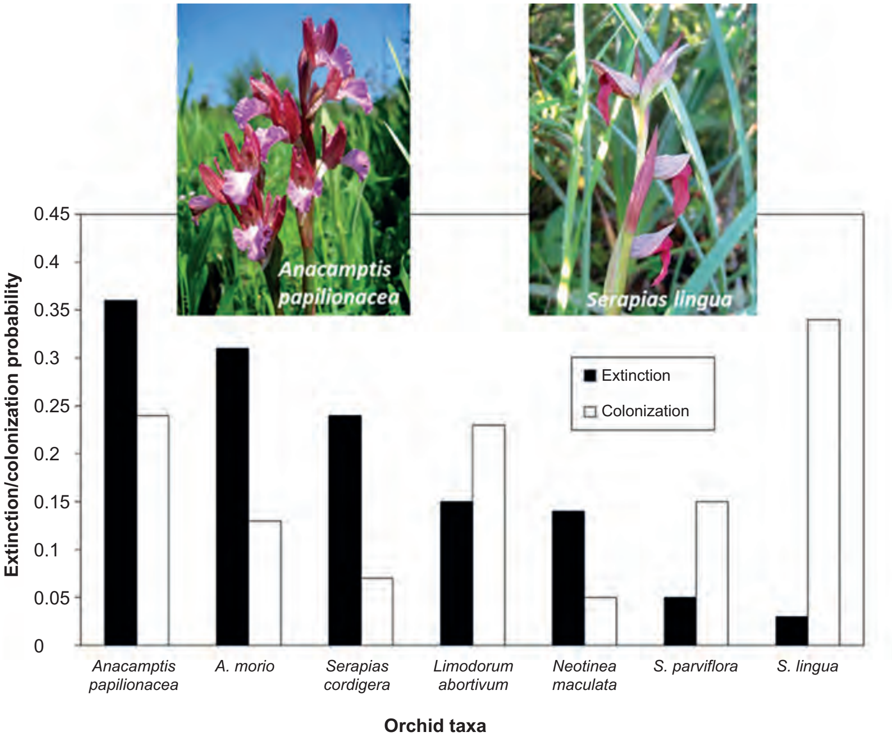


*Figure 2*
*Extinction and colonization probability (in %) of the most abundant orchid species sampled in Corsica, illustrated by photos of the two extreme species*
*Photos: P. Geniez.*

et al., 2006). This illustrates how biotic homogenization of assemblages at the local scale (loss of rare or specialized species) and the key role of biotic interactions determine biodiversity loss (Ekross et al. 2010; LeViol et al. 2012; Vogt-Schilb et al. 2015, 2016). It is therefore desirable that researchers in ecology and conservation biology continue their observations in different compartments of biodiversity worldwide so that they can be used as background data in the future.

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Chapter 5

# Health consequences in the Mediterranean region

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## Abstract

The Mediterranean basin is highly vulnerable to climate change, and a warming trend with changes in rainfall patterns with more heavy rains has already been observed. The frequency of dust storm and wildfire has also increased. Both non-communicable and communicable diseases will be seriously impacted by climate change since climate modification or air pollution influence the development of the former and weather conditions the latter. Different socio-economic characteristics within the Mediterranean basin will also exacerbate or on the contrary reduce health outcomes. Surprisingly few quantitative studies have explored the impacts of climate change on health in the Mediterranean region, and the few are geographically limited to specific areas of the basin.

Here we review the scientific literature on this topic and make some recommendations for the development of national and regional research, preparedness and adaptation policy in the Mediterranean region.



# Résumé

La zone méditerranéenne est très exposée aux changements climatiques, et un réchauffement régional de la température avec une modification du régime des pluies, généralement plus fortes, est actuellement observé. Les tempêtes de sable et les incendies non contrôlés sont en augmentation. Les maladies infectieuses et chroniques humaines peuvent être affectées par ces bouleversements de façon directe ou indirecte ; les conditions bioclimatiques conditionnent le développement des agents pathogènes et de leurs hôtes vecteurs ou réservoirs ; les modifications du climat ou la pollution atmosphérique qui en dérive ont une influence sur le développement de certaines maladies chroniques. Des déterminants, en particulier socio-économiques, prévalant ou en évolution dans la zone méditerranéenne affecteront aussi la santé de la population. Curieusement, peu de travaux scientifiques ont étudié les effets des changements climatiques sur la santé humaine dans la région, et les quelques rares études restent géographiquement limitées à des zones particulières du bassin méditerranéen. Dans ce chapitre, nous synthétisons la recherche réalisée dans le domaine, et proposons des recommandations en termes de recherches scientifiques nationales et régionales, et de stratégies de préparation et d'adaptation à ce nouveau contexte.

# Introduction

The consequences of global environmental changes for human health are among the top priorities of citizens worldwide. Climate change is one of many global environmental changes (land-use changes, ocean acidification, biodiversity loss, transcontinental trade and transportation, etc.), and there is ample evidence that it has already had significant effects on population health and additional consequences are expected in coming decades (McMichael et al. 2006, Costello et al. 2009). One of the critical issues is how and to what extent climate change, together with other associated environmental and social stressors, has consequences for the health of individuals and whole populations (Corvalan et al. 2005). Understanding such effects and possible interactions between different stressors is critical for effective public health decisions and strategies.

Climate change will have health effects worldwide, but here we focus on the Mediterranean region. Climate change has both direct and indirect effects on human health and both are relevant in this region. Direct effects include higher temperatures, increased UV irradiation and localized storms and floods. There is evidence that extreme temperatures are clearly associated with increased human mortality and morbidity, and recent findings show that heavy rainfall may accelerate the development of water-borne or vector-borne diseases. Indirect health effects are related to the deterioration of air, soil and water quality, which are expected to occur in the Mediterranean region. As an example, increased exposure to allergens, air pollution and infectious diseases that are related to climate change, will all significantly contribute to the increased frequency of respiratory diseases. Importantly, each of these indirect effects can also be triggered by other activities; for example, air quality is altered by climate change but also by industry, transportation, urbanization, etc. Concerning communicable diseases, many examples suggest a climate-driven cascade of effects model, notably a trophic one, for infectious disease outbreaks worldwide. Furthermore, interactions between climate change and the other stressors are very likely to take place and a major challenge will be to find out whether they act in an additive, synergistic or antagonistic manner. A major conclusion at this stage is that an assessment of the effects of climate change on health would be improved if it were combined with that of other environmental stressors (Flahault et al. 2015). Such an integrative approach is in line with the exposome concept and framework developed by Chris Wild from the IARC (Wild, 2005).

The duration and impact of heat waves are expected to increase with climate change. In a study on heat-related mortality rates in several European cities, Mediterranean cities including Barcelona, Rome and Valencia were found to be the most vulnerable to increased heat (Baccini et al. 2009). Similarly, the heat-related death rates in Lisbon are expected to increase significantly during the $21^{st}$ century (Casimiro et al. 2006). It is expected that these adverse effects will primarily affect vulnerable individuals, notably the elderly, who are more likely to suffer from chronic diseases (Oudin Åström et al. 2015). Another likely consequence is the increase in exposure to UV with its consequences for skin cancers. Modifications in atmospheric pollutants including ozone are discussed in the following subchapters.

Changes in the precipitation patterns are also expected with increased risks of floods and droughts. They may differ from one region/country to the other (Messeri et al. 2015). In addition to their direct effect on health notably through mosquitoes able to transmit tropical infections, these changes will most likely impact agriculture and the food supply, as described elsewhere in this book. There is reason for concern that it may eventually lead to a change in the Mediterranean diet, which is among the strongest assets in terms of health for the inhabitants of this region. It would be extremely deleterious if climate change were to alter the balanced nutritional habits of the Mediterranean population. While plans should be proposed to prevent the consequences of climate change in the Mediterranean area affecting diet, it is equally important to ensure the sustainability of the assets of this region, in particular food habits.

When examining the literature on climate change and health in the Mediterranean region, it is striking to see that very little work - a large proportion of existing literature consists of reviews and editorials, not original studies - has been carried out both on non-communicable and communicable diseases, and there are still many open questions (Hosking and Campbell-Lendrum, 2012). It is thus crucial to increase the number and quality of the studies and to highlight the importance of health effects in the future. It is also crucial that research is carried out not only in the northern part of the Mediterranean region but also on its southern and eastern rims. This will also contribute to a better awareness of the citizens of the prospects of climate change.

Climate change will affect the health of the Mediterranean populations both directly and indirectly. It should be included with other changes in population, migration and nutritional habits since the combination of those changes could lead to even more harmful conditions. We believe that if health concerns are highlighted by international bodies, the involvement of the citizens will be stronger and more sustainable. We also believe that the effects of all stressors and changes should be taken into consideration and integrated, and that the assets of the Mediterranean population, such as healthy diets, should be supported and advertised. In addition to preventive and precautionary actions, more research should be conducted to support national and trans-Mediterranean public health decisions.

# Climate change and infectious diseases in the Mediterranean region

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Concerning communicable diseases, it should be noted that, to date, the area surrounding the Mediterranean Sea has received little attention, and available datasets and results on the impacts of climate change on infectious diseases are few and far between (Navarra and Tubiana 2013). The effects of climate change on the spread and on the intensity of infectious diseases have been studied only in the countries along the north-western and western coasts of the Mediterranean Sea, whereas evidence is drastically lacking in the countries on the eastern and southern shores. These regions already face numerous humanitarian crises, from conflicts to natural hazards, and recent geopolitical changes, and climate change is likely to exacerbate the impacts on health. The Mediterranean climate and the proximity to the sea makes it attractive to people, which is resulting in a high rate of conversion of ecosystems for agricultural and other human uses with a parallel reduction in coastal wetlands and forests. As a result, the main constraint faced by the Mediterranean is linked to high population density and population growth, and the expansion of urban areas into peri-urban and rural landscapes. In addition, the risks for public health represented by emerging infections in the region due to the possible expansion of the range of some tropical vectors are an important source of concern widely reported in the media.

The Mediterranean region is known to be vulnerable to climate change, and a significant increase in mean temperature has been measured in the basin in recent decades. Extreme weather events have become more common with an increase in the frequency and severity of heavy storms like the "Cévennes episodes" in southern France or of heat waves on the western and southern ridges, parallel with a reduction in rainfall amounts. The projected decrease in precipitation in North Africa is also a major health concern because 22% of the world's water-poor population are concentrated in the Mediterranean region (Giorgi and Lionello, 2008). As a consequence of these ongoing changes, infectious diseases, being contagious or indirectly transmitted via a vector or a reservoir host or both, are expected to be affected. For some infections such as Chikungunya and West Nile viruses, climate change is still debated as the main driver of the increased risk of local transmission in the area, and for others, like many water- and food-borne diseases, the risk of spreading in the near future is real. Overall, adaptation to and preparation for changing patterns of infectious disease distribution in the Mediterranean basin is essential in the context of climate change.

Here, our aim is to identify the possible impacts of climate change on the emergence and spread of human infectious diseases in the Mediterranean basin, based on a review of the scientific literature. We limited our selection to evidence-based studies because, in most of the scientific literature, notably on vector-borne diseases, there still is remarkable confusion between climate-sensitive infections and diseases that are impacted by climate change (Guégan and Simard, 2015). We have different recommendations for individual Mediterranean countries and regional institutions, depending on their national or regional needs and vulnerability.

## Extreme events do matter in the emergence of infectious diseases in the Mediterranean region

*Vibrio parahaemolyticus*, *V. vulnifucus* and environmentally-persistent *V. cholera*e are halophilic bacteria that live in marine, lagoon and estuarine environments. These bacteria are recognized throughout the world as agents of gastroenteritis in human resulting from consumption of raw or undercooked seafood and serious infections caused by exposure of skin wounds to seawater (Esteves et al. 2015). Even if the pathogenic form of *V. cholerae* causing cholera appears to be absent from the Mediterranean Sea, there is a risk that pathogenic strains might be introduced. There is some scientific evidence showing that sea surface temperature is a major factor explaining the population dynamics of vibrios in coastal marine ecosystems, and that long-term effects of ocean warming should increase the dominance of these vibrios within the plankton-associated bacterial community (Vezzulli et al. 2012). However, a study conducted in French Mediterranean coastal lagoons in 2011 and 2012 showed that the highest concentrations in vibrios were in the Palavasian coastal lagoons, with an abrupt decrease in salinity caused by heavy rainfall and major flooding in the fall. These results clearly showed that flood events can have a major effect on the abundance of these environmentally-persistent bacteria in the lagoons of southern France. It is thus clear that harvesting shellfish from lagoons where the environmental conditions have changed significantly after flooding may represent a significant risk to public health in other sub-regions of the Mediterranean basin.

In September-November 2014, the French Health authorities reported a cluster of 11 autochthonous cases of Chikungunya disease in the city of Montpellier in the vicinity of a recently imported case. It has been demonstrated that the density of the female disease vector *Aedes albopictus* increased rapidly after the extreme "Cévennes episode", soon followed by an increase in the number of eggs collected in ovitraps (Figure 1). Observations suggest that the heavy rains after a period with little rainfall filled all the peridomestic containers where dessicated eggs of this mosquito were to be found, and that it was this situation that led to the increase in the number of mosquitos several weeks later (Roiz et al. 2015) (Figure 1). Before floods, accumulated temperatures are a good predictor of *Ae. albopictus* seasonal dynamics, but after accumulated rainfall over the four weeks prior to capture predicts the seasonal dynamics of this vector and extension of the transmission period of Chikungunya in Montpellier. This work presents the first evidence in support of a relationship between heavy rainfall and Chikungunya emergence in the Mediterranean region, and it goes against the common belief that heavy rainfall has a flushing effect on breeding sites, which in turn, negatively affects vector populations.

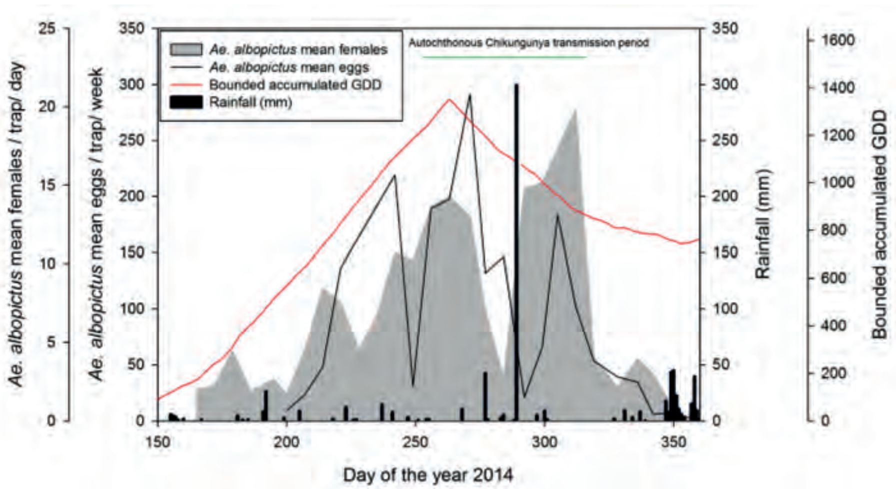


*Figure 1*
*Number of female* Aedes albopictus *tiger mosquitoes per trap per day (grey area) in different locations in Montpellier in 2014. Potential autochthonous Chikungunya transmission period (green line at the top of the figure). A massive rainfall event before day 300 was followed by a sharp increase in the number of female mosquitoes.*
PLoS Neglected Tropical Diseases *(2015). doi:10.1371/journal.pntd.0003854*

Taken together, these two illustrations clearly show that for water-borne and vector-borne infectious diseases, it is crucial to take extreme events into account in research on climate change and health. This is obviously the case for environmentally-persistent aquatic bacteria, but the same could be true for aquatic viruses that cause enteritis in human (and mass mortality in seafood mollusks; heavy rainfall can modify environmental conditions by decreasing water salinity, thus supporting the population dynamics of vibrios. Concerning vector-borne diseases, these extreme events may extend the period of infection transmission to human. These changes may increase the impact of many water-borne diseases like enteric fever, and vector-borne diseases like the West Nile virus, which are already problematic in the Mediterranean region (Vittecoq et al. 2013). Although very few cases of cholera have been reported in the Mediterranean basin in recent years (WHO 2016), *V. cholerae* was recently isolated from freshwater, water in coastal areas, and from seafood in European and North African countries (Eddabra et al. 2011; Senderovitch et al. 2010; Vezzulli et al. 2010). Recent geopolitical changes together with an increasing number of refugees fleeing ongoing conflicts in North Africa and the Middle East might generate favorable conditions for new cholera outbreaks, which often occur in overcrowded settlements. In this section, we do not review the impact of flushing caused by heavy rains, which may transport waste to the nearest stream, which, in turn, flows into larger rivers or into coastal lagoons and ends up in human populations. Human and animal waste contain bacteria, viruses and fungi that can be harmful to human, and their concentration may increase in the near future due to extreme flooding events interacting with failing sewage infrastructure.

# Long term warming and infectious diseases in the Mediterranean region

## Climate-sensitive diseases does not mean climate-change sensitive

As mentioned above, abiotic and biotic conditions in the environment determine the distribution of vector- and reservoir-borne diseases in that they influence the vector (or reservoir)-host-pathogen transmission cycle, including vector or reservoir distribution, abundance and diversity. Vector or reservoir host spatial distribution is constrained by the distribution of appropriate habitats, for instance, aquatic environments that support the development of larvae, and by the factors that determine adult mosquito habitats. However, not only the distribution of water for mosquito or rodent habitats needs to be taken into consideration but many other environmental parameters, for instance the vegetation type and cover. It is also important to take meteorological conditions into account in vector- and reservoir borne infections, and many studies have shown that the distributions of mosquito or rodent species are determined by winter and summer temperatures, precipitation patterns and most important, photoperiod (Guernier et al. 2004). Apart from mean temperature or precipitation values, minimum threshold values are also important as limiting factors for the development of the disease life cycle. Of course, other ecological and human factors may also influence the distribution of vector and reservoir populations, such as land use/land cover, urbanization or human population density. Climate influences different aspects of the vector (or reservoir)-host-pathogen system, and the potential impact of global warming on these diseases is still the subject of controversy (Guégan and Simard, 2015). In general, researchers consider that the effects of climate change, say an increase in mean temperature, will linearly affect mosquito distribution, abundance and longevity, pathogen incubation period and replication, and their interactions. Previous studies indeed concluded that high temperature and rainfall are positively associated with mosquito abundance, and hence with disease outbreak and spread, which is a simplistic view of disease transmission.

A recent survey conducted in the Doñana National and Odiel Natural Parks in south-west Spain by Roiz et al. (2014), based on data collected over a period of 10 years (2003-2012) consisting in bi-weekly surveys of seven mosquito species known to transmit West Nile virus, Usutu virus, dirofilariasis and *Plasmodium* protozoans, showed that the effects of climate and climate variability are species-specific, site-specific, time-dependent and are by essence non-linear in their reaction. Weekly temperatures are related to seasonal abundance patterns in the two mosquitoes *Culex pipiens* (a vector for West Nile and Rift Valley viruses) and *Ochlerotatus caspius* (a vector for West Nile and Tahyna viruses, and tularemia) while accumulated (1-4 weeks before) temperatures were shown to be positively correlated with *Cx. modestus* (a vector for West Nile and Tahyna viruses, and tularemia) and *Cx. perexiguus* (a vector for West Nile virus) abundances. On the contrary, accumulated temperatures were negatively correlated with *Cx. pipiens* and *O. detritus* abundances. These results clearly show that climate change will not necessarily lead to an increase in mosquito populations, and that over-simplified statements assuming that higher temperatures (or rainfall) lead to more mosquitoes, and hence increase the risk of epidemics, are not appropriate and overestimate the effect of climate change on real disease risks in the Mediterranean region (Guégan and Simard, 2015). Interestingly, this study showed that it is essential to carry out a careful analysis of temporal patterns of vector species in field data in order to analyze short, medium and long temporal trends and then distinguish the role played by climate variability and change from other important parameters in disease transmission. In any case, it is not possible to extrapolate from conclusions regarding climate change and mosquito abundances to the risk of disease outbreaks in the Mediterranean basin and elsewhere (Guégan and Simard, 2015). Recent modeling advances used to analyze the spread of mosquito species have shown for the tiger mosquito *Ae. albopictus* in southern France that human activities, notably transportation, are especially important for mosquito dispersion while land use appears to be a major factor influencing mosquito establishment, not climate change *per se* (Roche et al. 2015a). Monitoring and modeling both extreme events and long-term climate drivers of infectious disease outbreak and spread can help to anticipate, or even forecast, an upsurge of infections in the Mediterranean.



## Some infectious disease study-cases in the region

The Mediterranean region has undergone several social, economic, political and environmental changes in recent decades. Wars have occurred in the Middle East and several countries in North Africa have experienced social and political instability and coups d'état. Many surrounding countries in both regions have also experienced wars, social instability, human migration, refugees, poor sanitation, and a low level of hygiene, with a high risk of consuming contaminated food or drinking water (Habib et al. 2010). Overall, all around the basin, increasing urbanization and human population density in coastal areas are critical in exacerbating air pollution and in creating ideal foci for the transmission of many contagious illnesses including diarrheal diseases and indirectly-transmitted diseases like dengue or Chikungunya virus infections. Natural environmental changes (warm temperature, less or heavy rainfall, longer periods of drought and extreme events) and human activities (transcontinental transportation of goods, animals and people within the basin, the disappearance of natural wetlands, coastal planning, dam construction on large Mediterranean rivers), all these changes may have enhanced natural cycle transmission of infectious agents. In this section, based on Rodríguez-Arias and collaborators' technical report (2008), we briefly review the emerging infectious diseases that pose serious health problems in the Mediterranean region. For eastern Mediterranean countries, Habib et al. (2010) and Khader et al. (2015) reviewed studies reporting the impacts of climate change on health or studied associations between meteorological parameters and human health outcomes, and the reader is invited to consult these references. Table 1 gives an overview of other potential infectious disease threats that could emerge in the near future in this area.

Visceral leishmaniasis is endemic around the Mediterranean basin and represents the main form of the disease. Countries on the northern rim of the basin like Spain, France, Italy, the Balkan sub-region, and Greece are where the disease transmission occurs. Generally, leishmaniasis occurs in rural areas, villages in mountainous regions and also in some peri-urban areas where dogs act as hosts for the disease life-cycle. This disease system is climate-sensitive, and strongly affected by changes in rainfall, temperature and humidity patterns. Global warming and land degradation together affect the epidemiology of leishmaniasis in a number of ways. According to WHO, changes in temperature, rainfall and humidity can have strong effects on sandfly vectors and reservoirs of rodent hosts by altering their distribution and influencing their survival and population size. Likewise, small modifications in temperature can have a profound effect on developmental cycle of *Leishmania* promastigotes in sandflies, thus supporting the development of the disease life-cycle in new as yet uncolonized areas. Finally,

*Table 1*

*Climate-sensitive infectious diseases in the Mediterranean area and potential risk of emergence and spread. An asterisk means that since the information was originally published, cases have been detected in the area. Nota from the authors: "climate-sensitive diseases" does not mean that a formal demonstration of an effect of climate change has been demonstrated on the different listed diseases so far. These evidence-based studies of an effect of climate variability and change on the corresponding diseases were carried out at global scale. Modified from Rodriguez-Arias et al. (2008).*

| Infectious disease | Already present in the Mediterranean | Number of papers published (2007-2010) | Evidence for an effect of climate variability and change |
|---|---|---|---|
| ***Food- and water-borne*** | | | |
| Amoebiasis | Yes | 4 | No |
| *Campylobacter* enteritis | Yes | 12 | No |
| Cholera | No (potential risk) | 9 | Yes (South Asia, north-west South America, West Africa) |
| Cryptosporidiosis | Yes | 22 | No |
| Diphyllobothriasis | Yes | 2 | No |
| *Escherichia coli* infection | Yes | 10 | No |
| Food-borne *Vibrio* enteritis | Yes* | 25 | Yes (North Sea, Baltic, Atlantic Ocean, Mediterranean Sea) |
| Giardiasis | Yes | 17 | No |
| *Legionella* infection | Yes | 17 | No |
| Leptospirosis | Yes | 21 | No |
| Rotavirus enteritis | Yes | 7 | No |
| *Salmonella* infection | Yes | 24 | No |
| Schistosomiasis | Yes | 3 | No |
| Shigellosis | Yes | 6 | No |
| Strongyloidiasis | Yes | 1 | No |
| Typhoid and paratyphoid fevers | Yes | 7 | No |
| ***Air/human to human transmission*** | | | |
| Meningococcal infection | Yes | 24 | Yes (West Africa) |
| ***Vector-borne*** | | | |
| Typhus fever | Yes | 12 | No |
| Chikungunya virus disease | Yes | 25 | No |
| Dengue and dengue hemorrhagic fever | Yes* Some doubts | 14 | Yes (South-East Asia, northern South America) |
| Malaria | Yes | 13 | Yes (South-East Asia, East Africa, northern South America) |
| Rift Valley fever | Yes | 6 | Yes (South Africa) |
| West Nile virus infection | Yes | 40 | No (controversies) |
| Plague | Yes* | 4 | Yes (Central Asia) |
| Leishmaniasis | Yes | 31 | Yes (Southern Europe, South America) |
| Sandfly virus fever | Yes | 15 | No |
| Crimean-Congo hemorrhagic fever | Yes | 24 | No |
| Lyme disease | Yes | 34 | Yes (Northern Europe) |
| Spotted fever | Yes | 21 | No |
| Tick-borne relapsing fever | Yes | 2 | No |
| Tick-borne viral encephalitis | Yes | 13 | No |
| Tularemia | Yes | 4 | No |
| Filariasis | Yes | 4 | No |

extreme climatic events and famine resulting from climate change can lead to massive displacement and migration of people to infected areas. Nowadays, we have a very limited understanding of the impact of climate change on leishmaniasis (re-)emergence and spread within the Mediterranean basin even if observations in southern France and northern Italy are congruent in showing the existence of a northwards colonization front. Local modifications in the environment like in Israel have favored the spread of rock hyrax colonies (*Procavia capensis*) close to human habitations, thereby establishing zoonotic transmission of *Leishmania (Leishmania) tropica*. Other concerns include the potential establishment of *Le. tropica* in Sicily, where the vector *Phlebotomus (Paraphlebotomus) sergenti* is locally abundant (Bates et al. 2015). In addition to the environmental risk factors for leishmaniasis transmission, urbanization, social instability, low hygiene education, inadequate housing and sanitation, domestic zoonosis involving dogs and HIV co-infection are important factors in leishmaniasis epidemiology.

The West Nile virus outbreaks that occurred in Romania (1996) and Israel (2000) followed a drought season, and the role of meteorological conditions is clearly important in the development and spread of this virus in the Mediterranean region. After high rainfall followed by a period of drought, pools become richer in organic materials and sediments from which *Culex* vector mosquitoes (see above) may benefit, thus extending their breeding season. These conditions are then optimal for bird species to congregate around rich pools with myriads of mosquitoes. The conditions are met for the virus to circulate easily (but see comments above about extreme events). In addition, warm temperature accelerates the extrinsic incubation period of viruses within mosquito carriers, and thus enhances the potential for transmission and dissemination (Conte et al. 2015). However, West Nile virus disease is a complex disease system where many parameters may act independently or synergistically (Chevalier et al. 2014, Roche et al. 2015b), and further studies are clearly needed in the Mediterranean to determine the exact role played by climate change in the observed emergence and spread of this disease (see Di Sabatino et al. 2014 for a recent review and Conte et al. 2015 for a time and space analysis of suitable habitats in the Mediterranean region and central Europe). Notably, habitat alteration and the disappearance of wetlands with increasing urbanization all around the basin might have profoundly modified bird species behavior and ecology.

In recent years, malaria has re-emerged in residual foci in Eastern Europe and the present climate change could actually increase mosquito vectorial capacity, especially in southern countries of Europe and the Mediterranean region. Malaria was endemic in Europe and the Mediterranean until the mid-20$^{th}$ century, but was considered eradicated on the northern rim of the Mediterranean Sea in the 1960s and 1970s. Southern Europe is among the most risky regions for malaria resurgence, especially for *P. vivax* malaria resurgence due to its climate characteristics, the proximity to Africa and Caucasus, and the presence of a range of more or less potential Anopheline vectors (Odolini et al. 2012). *Anopheles atroparvus* is known to be an efficient malaria vector and it is widely distributed in Europe, except in some Mediterranean regions including southern Italy, Greece and Turkey where *An. labranchiae* and *An. superpictus* are the dominant species. Studies on the receptivity of the European vector *An. atroparvus* revealed that it is not susceptible to the afro-tropical *P. falciparum* strains, which represents the dreadful killer of malaria forms, but is probably fully susceptible to infection by *P. vivax* strains imported from Africa. Since 2004, Morocco is considered to be malaria-free, but imported malaria cases in the northern central region highlights the potential risk of introduction of the parasite in this region. In summer 1997, one autochthonous *P. vivax* case occurred in Italy, in a rural zone where *An. labranchiae* occurs, and the same happened in Corsica in August 2006, where a case of indigenous *P. vivax* malaria - the first case of autochthonous transmission in France since 1972 - was diagnosed. Four years later, in 2010, Spain reported the first indigenous cases of *P. vivax* malaria in the province of Aragon, where the vector *An. atroparvus* is present. Then, in August 2011, a *P. vivax* infection was diagnosed in a Romanian traveler returning from Greece. Greece was officially considered malaria-free in 1974, but sporadic autochthonous cases were reported in 1991, 1999 and 2000 (Odolini et al. 2012). Recent studies in the Ebro delta in Spain, an historically endemic malaria area, showed that this ecosystem currently presents ecologically favorable characteristics, notably with the presence of *An. atroparvus* and its rice field landscape, for the re-appearance of malaria if an appropriate malaria strain were to be introduced and the extension of the potential transmission period due to ongoing global warming (Sainz-Elipe et al. 2010).

At present, there is concern about the possible emergence and spread of *Aedes*-borne viral diseases in the Mediterranean region. Dengue fever is the most important one, and dengue outbreaks were rather common in the Mediterranean at the beginning of the 20$^{th}$ century (Rezza 2016). Several epidemics also occurred in the 18$^{th}$ and 19$^{th}$ centuries in ports in the eastern Mediterranean and occasionally in the northern and western parts (Schaffner and Mathis 2014) (Table 2). The vector *Ae. aegypti* was re-introduced locally by vessels at that time and was widely present in southern Europe. Notably, the last major outbreak occurred in 1927/1928 in Athens and neighboring districts in Greece with a peak in August 1928 that affected more than 1 million people, and then left Mediterranean Europe. In September 2010, two cases of dengue were identified in Nice, southern France, and in the summer of the same year, another transmission event was detected in Croatia between August and October, 2010. Again, in 2013 and 2014, five autochthonous cases were identified in southern France in Bouches-du-Rhône and Var Departments. More recently, autochthonous cases of dengue were reported in Nimes, southern France (Succo et al. 2016). Since 2010, at least 23 cases of dengue have been reported by public health authorities in Mediterranean Europe. Chikungunya is another *Aedes*-borne viral disease threatening the health of Mediterranean citizens. In the summer of 2007, more than 250 cases of Chikungunya virus disease occurred in the north-east of Italy, and in September 2010 autochthonous transmission of the virus was identified in south-east France, in both situations, with primary cases returning from a visit in India (Rezza et al. 2007). In the Mediterranean area, *Ae. albopictus* (the main established vector) appears to be the vector implicated in all transmission events for dengue and Chikungunya. Nowadays, with the large epidemic of Zika virus, there is a possibility of an increased risk of Zika virus transmission within the Mediterranean basin during the summer season. However the risk of large scale outbreaks and endemicity for these *Aedes*-borne infections in the Mediterranean appears to be rather low. Climate change, which may favour overwintering of virus and mosquitoes in the region, is not the only driving factor that influences disease spread, and outbreaks caused by *Ae. albopictus* are less important than those due to its congener, *Ae. eegypti*, due to its feeding habits. In general, other important drivers of dengue transmission are socio-economic factors, including globalization, urbanization, and anthropological or social human behaviors. Nevertheless, the presence of *Ae. aegypti* now established on the Caucasian cost of the Black Sea, is less reassuring today (Schaffner and Mathis 2014).

*Table 2*

*Historical and contemporary outbreaks of dengue fever in the WHO European region. Note that most of infected localities are in the Mediterranean region except the Canary Islands and Madeira in the Atlantic Ocean and Vienna, Austria in mainland Europe. From Schaffner and Mathis (2014).*

The Lancet Infectious Diseases.

| | Location | Notes |
|---|---|---|
| 1784, 1788, 1793 | Cadiz, Seville (Spain) | End of first pandemic, 1779–84 |
| 1861 | Cyprus | – |
| 1863, 1867 | Cadiz (Spain), then Jerez, Seville, and other places in Andalusia | Imported from the West Indies by troops |
| 1865 | Canary Islands (Spain) | – |
| 1881 | Crete (Greece) | Half of the inhabitants affected |
| 1887 | Gibraltar | Fifth pandemic, 1887–89 |
| 1888–1889 | Cyprus | – |
| 1889 | Athens, Piraeus, Salonica (Greece), Greek Islands (Rhodes, Chios, and others), southern Turkey, Izmir, Manisa to Istanbul, Trabizon (Turkey), Varna*(Bulgaria), Lisbon (Portugal), Israel | Around 80 000 cases in Izmir (80% of the inhabitants) |
| 1889–1890 | Istanbul, Izmir (Turkey), Napoli (Italy) | – |
| 1895–1897 | Athens (Greece) | – |
| 1899 | Antalya (Turkey) | – |
| 1910 | Athens, Piraeus (Greece) | – |
| 1912 | Israel | – |
| 1913 | Cyprus | – |
| 1916 | Dardanelles, Trabizon (Turkey) | – |
| 1921 | Vienna*(Austria) | – |
| 1927 | Malta | – |
| 1927–1928 | Piraeus, Athens, Euboea, Gulf of Aegina (Greece), Izmir to south of Rhodes (Turkey), Israel, Greece: DEN-1 and DEN-2 confirmed by retrospective serological study | More than 1 million of people affected (90% of the population in Athens); 1000–1500 deaths |
| 1928 | Cyprus, Andalusia | – |
| 1929 | Izmir | – |
| 1929–1933 | Greece | Confirmed by retrospective serological study |
| 1945 | Turkey, Israel (and other Middle East countries) | – |
| 2010 | Croatia; three DEN-1 clinical cases (including one reported in Germany) plus 15 recent infections | Virus probably introduced from Indian subcontinent |
| 2010, 2013 | France; DEN-1 cases (2010), one DEN-2 case (2013) | Viruses probably introduced from West Indies |
| 2012–13 | Madeira; more than 2200 DEN-1 cases from October, 2012, to January, 2013, plus 74 cases reported from Portugal mainland and 12 other European countries | Virus probably introduced from Venezuela |

DEN-1=dengue virus serotype 1. DEN-2=dengue virus serotype 2. *Not clear whether data refer to a dengue outbreak or imported cases only, as there is no indication for the presence of A aegypti in Varna and Vienna.

***Table*: Historical and contemporary outbreaks of dengue in the WHO European region**

# Research initiatives needed on communicable diseases for the future

To conclude this section, one personal observation that can be made compared to other regions of the world where climate-sensitive diseases have been studied is that studies on climate change and infectious diseases in the Mediterranean are sporadic, unfocused and often anecdotic from a data-orientated perspective, and too uncoordinated to make it possible to answer the question concerning the impacts of climate change on health. Habib (2011) made the same comment concerning chronic illnesses and socially situated health outcomes particularly impacted by climate change in the Eastern Mediterranean region. In general, studies do not formulate their findings within a conceptual framework that links them to climate change, but discuss how weather variations (which are not necessarily climate change indicators; see comments above) such as temperature, humidity and rainfall impact infectious diseases and their hosts. Concerning vector-borne diseases more specifically, most studies discuss the presence and development of a given potential vector species and the extension of its survival period, and very rarely or never analyze the association between the vector, the pathogen and the environment, and the possible changes in these interactions due to climate change (Guégan and Simard 2015). Longitudinal studies over extended periods of time and at different sites that investigate the link between climate change and infectious diseases are absolutely indispensable in the Mediterranean region since these studies represent the gold standard in climate change impact research today (Rodó et al. 2002, Morris et al. 2014). There is an absolute need for longitudinal studies to be extended to include more countries in the region and to include other environmental, ecological, social and economic factors that might affect the spread of the disease. Research on health outcomes of climate change requires multidisciplinary knowledge of complex and multi-layered environmental, social, economic, political and health processes, and it definitely requires the establishment of a strong trans-Mediterranean medical research and health coordinating body.

According to Navarra and Tubiana's (2013) book, the European Community funded FP6 Emerging Diseases in a changing European eNvironment (EDEN) integrated research program was an excellent opportunity to bring together researchers from different disciplines in Europe, Northern Africa and Turkey to develop systematic assessments of localized environmental, economic, demographic and health impacts of climate change on emerging infectious diseases. Even if this EC research initiative was not only focused on the Mediterranean region, a substantial part of the research activities were conducted in the Mediterranean basin, notable on leishmaniasis, malaria, tick-borne diseases, and West Nile virus and Rift Valley virus diseases.

# The impacts of climate change on non-communicable diseases in the Mediterranean region

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According to the existing literature (Suk and Semenza 2011), climate change will increase the incidence of non-communicable diseases (NCDs), including cardiovascular disease (CVD), respiratory diseases, some cancers, mental disorders, injuries, and malnutrition and overall poor health among all populations through direct and indirect effects (see Table 1).

A number of studies have shown that the elderly, children, people with pre-existing chronic conditions (i.e. respiratory diseases, CVD, diabetes) and individuals with a low socio-economic status, are at higher risk of suffering from climate change effects.

## Extreme weather and related events have direct health effects in the Mediterranean region

The frequency of extreme natural hazards and weather events including heat waves, cold spells, floods, storms and droughts has been increasing in recent decades in Europe and specifically in the Mediterranean region due to climate change. Among them, the key climatic change factors that directly influence NCDs are extreme temperature events, barometric pressure, floods and storms (see Table 1).

Since the 1960s, the Mediterranean region has become warmer with a significant increase in the frequency, intensity and duration of heat waves (Kuglitsch et al. 2010) and of related health effects. In the 'Assessment and Prevention of Acute Health Effects of Weather Conditions in Europe (PHEWE)' project, including Mediterranean cities, high temperatures had a specific impact on respiratory admissions, particularly in the elderly population (Michelozzi et al. 2009). This is because, among elderly, the body temperature increases with the mean outdoor temperature. Heat effects are also observed in children (Iñiguez et al. 2016), for whom hospitalization for natural causes rose significantly with heat in Rome and Valencia between 2001 and 2010. Patterns of delays and critical windows of exposure varied according to the outcome considered with respiratory and gastrointestinal diseases being the leading causes for short and long-term lags respectively. Less expected are the effects of cold spells that belongs to the kind of extreme events whose frequency is increasing due to climate changes. In adults, winter deaths are due to influenza, coronary thrombosis and respiratory diseases. Coronary thrombosis deaths peak about two days after the peak of a cold spell whereas respiratory disease, namely pneumonia and COPD exacerbations, peak about 12 days after the peak cold. The rapid coronary deaths are due mainly to haemoconcentration resulting from fluid shifts during cold exposure; some later coronary deaths are secondary to respiratory disease. In Italy, excess deaths among the elderly were recorded in the 14 cities that suffered from a cold spell in February 2012 (de Donato et al. 2013). Cause-specific analysis showed a statistically significant excess in mortality for respiratory disease, COPD, cardiovascular disease, ischemic heart disease. Similar results were reported for emergency room visits. In the PHEWE project mentioned above (Michelozzi et al. 2009), a decrease in temperature was associated with an increase in the daily number of total natural deaths and specifically with an increase in cardiovascular, respiratory, and cerebrovascular deaths, respectively. The increase was greater among older age groups. The cold effect was found to be greater in warmer (southern) cities and persisted up to 23 days, with no evidence of mortality displacement (Analitis et al. 2008). A recent study in the Czech Republic investigated differences in the effects on acute and chronic diseases following extreme cold and hot temperature (Davídkovová et al. 2014). While excess deaths due to ischemic heart disease (IHD) during hot spells were mainly of persons with chronic diseases whose health had already been compromised, cardiovascular changes induced by cold stress may result in deaths from acute coronary events rather than chronic IHD, and this effect was also important in the younger population. This suggests that the most vulnerable population groups as well as the most affected cardiovascular diseases differ between hot and cold spells, which needs to be taken into account when designing and implementing preventive actions.

*Table 1*
*Direct and indirect effects of climate change on non-communicable diseases (NCDs).*

| **Climate change effects** | | **Additional factors contributing to the indirect effect** | **NCD** | **Direction of the risk** |
|---|---|---|---|---|
| *Direct:* | *Indirect:* | | | |
| Heat extreme | | | CDV and respiratory morbidity and mortality | Increase |
| Cold extremes | | | Cardiorespiratory morbidity and mortality | Increase |
| Low atmospheric pressure during storms | | | ISP | Increase |
| Extreme weather events (floods, storms, etc.) | | | Injury, Impaired mental health, Impoverishment | Increase |
| Storms | | Pollen breaking | Asthma | |
| Drought | | | Malnutrition, Impaired mental health | Increase |
| Pests | | Increasing use of pesticides | Asthma, Parkinson's disease, Cancers | Increase |
| Aflatoxin (fungal metabolite) | | Cereal contamination | Liver cancer | Increase |
| Increased temperature, windless conditions | Higher ground-level ozone | Urbanization | Increased respiratory tract irritation, CDV and chronic pulmonary disease hospitalizations, and lung disease mortality | Increase |
| Wildfires, drought | Higher Particular Matter level | Urbanization | COPD exacerbations, Mental illness | Increase |
| Altered trajectory of recovery of stratospheric ozone with changes in precipitation and cloud coverage | Altered ambient ultraviolet radiation (UVR) | | Skin cancer<br>Autoimmune diseases (multiple sclerosis) | Increase<br>Decrease |
| Global warming | Higher pollen counts and allergenicity | Longer pollen season, modified pollen distribution | Allergic rhinitis (hay fever) and asthma | Increase |
| Floods | More molds | | Allergic rhinitis, sinusitis and asthma, hypersensitivity pneumonitis, mycotoxin toxicity | Increase |

*: in temperate zones including Mediterranean zones
ISP: Idiopathic spontaneous pneumothorax

The frequency of heavy precipitation and flooding events is likely to increase or to become more intense as a result of climate change in the Mediterranean region (see corresponding section). In the past decades, in Europe and specifically in the Mediterranean areas, they caused damage to properties, personal injuries, enteric infections, increase in mental health problems (anxiety, depression, sleeplessness, deaths or post-traumatic stress syndrome), and potential contamination by toxic chemicals in exposed and vulnerable people (Messeri et al. 2015). Unexpectedly, although the risk of death most obviously increased during the period of flooding, a controlled study of the 1969 floods in Bristol, United Kingdom, reported a 50% increase in all-cause deaths in the flooded population in the year following the flood, most pronounced among those aged 45-64 years.

In addition there is an increasing body of evidence for the occurrence of severe asthma epidemics during thunderstorms in various geographical zones including in the Mediterranean region (D'Amato et al. 2016). The main hypotheses explaining association between thunderstorms and asthma claim that thunderstorms can concentrate pollen grains and molds spores at ground level due to atmospheric pressure, which may then release allergenic particles of respirable size in the atmosphere after their rupture by osmotic shock. The pressure has been involved also in idiopathic spontaneous pneumothorax (ISP). Variations in the atmospheric pressure have been involved in the initiating mechanisms (rupture of lung blebs, bullas or damaged alveolar walls) of ISP due to increased trans-pulmonary pressure during storms (Alifano et al. 2007).

## Chemical and biological air pollutants have indirect effects on health in the Mediterranean region

Climate change also increases the likelihood for individuals to be exposed to chemical air pollutants and bio-contaminants like viruses, bacteria, pollens and molds, which are established causes of NCD incidence or exacerbation (Table 1) (Ziska and Beggs 2012).

Climate change can affect air quality and *vice versa* air quality can impact climate change because many air pollutants are greenhouse gases due to human activities and natural phenomena (Ayres et al. 2009). Extra sunlight and higher temperatures due to global warming will lead to longer episodes of ozone peaks, generally in large cities. Higher concentrations of gases and particles are expected due to increased human activity and traffic in large cities where in the long run, a large majority of the world population will be forced to live as a result of climate change related factors, sea level rise among others. Air pollution has been linked to a broad spectrum of NCDs (diabetes, cardiopulmonary diseases, neurodegenerative diseases, etc.). High levels of vehicle emissions and westernized lifestyle have been correlated with increased aggravation of NCDs (Baldacci et al. 2015). Important data for the Mediterranean area result from *ad hoc* case studies (Baldacci et al. 2015). Among them, the European MED-PARTICLES project, which followed up climate, air pollution and health in 10 European Mediterranean metropolitan areas from 2001 to 2010. MED-PARTICLES findings provide support for short-term effects of $PM_{2.5}$ on mortality due to diabetes, cardiac causes, COPD, and to a lesser extent to cerebrovascular causes, in the European Mediterranean region (Samoli et al. 2014). Several PM constituents originating from different sources, were involved in the relationships between PM and hospital admissions in the Mediterranean area (Basagaña et al. 2015). In particular, black carbon (BC), which in western industrialized nations derives primarily from diesel engines and biomass burning, is a significant public health burden, particularly in European cities with high traffic density (Ostro et al. 2015). In addition, epidemiological and toxicological research suggests a causative relationship between air pollution and the increased incidence of NCDs although no specific data are available for the Mediterranean region due to the absence of longitudinal studies (Ahn 2014, Baldacci et al. 2015). This is why air pollution is considered to be one of the factors that may explain the increase in allergic and respiratory diseases and their worsening over recent decades.

In addition to anthropogenic air pollution, natural air pollution also constitutes a real danger for the people living within Mediterranean area. The concentration of particles will increase because of desertification and wildfires (D'Amato et al. 2015).

The number of wildfires has increased dramatically in Europe (Youssouf et al. 2014). In the Mediterranean area, forest fires usually occur during spring and summer, they overlap with Saharan outbreaks, are associated with increased temperature and their health effects are mostly due to an increase in particulate matter. Based on the literature, various studies have established the relationship between $PM_{10}$ and $PM_{2.5}$ and cardiorespiratory symptoms in terms of emergency room visits and hospital admissions (Youssouf et al. 2014). Associations between wildfire emissions and various subclinical effects have also been established. However, few relationships between wildfire emissions and mortality have been observed (Youssouf et al. 2014). Certain segments of the population may be particularly vulnerable to smoke-related health risks. Among them, people with pre-existing cardiopulmonary conditions, the elderly, smokers and, for professional reasons, firefighters. Surveillance of wildfires and $PM_{10}$ in 10 southern European cities in Spain, France, Italy and Greece (2003-2010) using satellite data showed that smoke was associated with increased cardiovascular mortality in urban residents, and $PM_{10}$ on smoky days has a larger effect on cardiovascular and respiratory mortality than on other days (Faustini et al. 2105).

In addition, outbreaks of Sahelo-Saharan dust over Mediterranean areas are frequent and often exceed the European Union's 24-hr standard of 50 $\mu g/m^3$ for $PM_{10}$. Evidence for the effects of coarse particles ($PM_{2.5-10}$ and $PM_{10}$) on natural and cause-specific mortality, with stronger estimated effects on cardiac mortality has been collected during dust outbreaks in Rome (Mallone et al. 2011). Identification of $PM_{10}$ originating from the desert through satellite images confirmed a positive association with mortality and hospitalizations in Southern Europe. Recent experimental work confirmed that the redox activity of particles is amplified by ozone, raising the possibility of a three-way interaction between particles, ozone and temperature in the future. The situation is particularly alarming in the Mediterranean area as shown by peaks of ozone and desert storms.

Excessive exposure of the skin to the sun causes skin cancer (Lucas et al. 2015). Solar irradiation also induces systemic immune suppression that may have adverse effects on health, such as through the reactivation of latent viral infections, but even beneficial effects through suppression of autoimmune reactivity. UV-B irradiation of the skin is the main source of vitamin D that plays a critical role in the maintenance of calcium homeostasis in the body in many geographic locations (Lucas et al. 2015). These dual results make it difficult to provide public health messages to guide safe exposure to the sun except that excessive exposure should be avoided.

Floods following extreme weather events and related humidity can lead to mold allergies and the development of asthma in susceptible individuals (D'Amato et al. 2015).

Lastly, climate is at the origin of a change in the geographic distribution of some plants, earlier onset and extension of the pollen season, and increased production of pollen and pollen allergens by the same plant due to the effect of the temperature (D'Amato et al. 2007). New plants can also arrive. Recent trends to warmer summers and increased volumes of international trade have accelerated the ragweed invasion notably. All these phenomena greatly increase the risk of allergic sensitization and of the development of asthma and allergic rhinitis.

Since airborne allergens and air pollutants frequently increase simultaneously in the atmosphere, enhanced IgE-mediated response to aeroallergens and enhanced airway inflammation could account for the increasing frequency of respiratory allergy and asthma in atopic subjects in the last five decades. Observation data show that exposure of pollens to high concentrations of air pollutants significantly increases their fragility and disruption, leading to subsequent release of pollen cytoplasmic granules into the atmosphere (D'Amato et al. 2015), which could increase the incidence of allergic airway disease in sensitized individuals by facilitating the bioavailability of airborne pollen allergens. Experimental data highlight a direct influence of elevated $NO_2$ on the increased allergenicity of ragweed pollen (Zhao et al. 2016). Climatic factors (temperature, wind speed, humidity, thunderstorms, etc.) can affect both components (biological and chemical) of this interaction.

## Non-communicable disease concerns in the future

In Europe, an increase in the frequency and intensity of summer heatwaves is expected, especially in central, eastern and southern countries (McMichael et al. 2006). These changes will increase the burden of diseases and of premature deaths, particularly in population subgroups with limited adaptive capacity, such as the elderly and patients with COPD, but statistics on populations in different climates suggest that, given time, people will adjust to global warming with little change in either mortality. In contrast, global warming can be expected to reduce flu related deaths, especially in the case of people suffering from pre-existing NCDs. The number of extreme meteorological events will also increase. Pollens and molds will rise and engender allergic morbidity. Molds can also be at origin of other morbidities. Current indications are that air pollution will remain the main environmental cause of illness and death in the Mediterranean region, but these events are hard to differentiate from the morbidity and mortality due to the weather and other factors, and clear identification of air pollution deaths and diseases may need more extensive data than is currently available in the Mediterranean.

# Final remarks and recommendations for the future

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## Main remarks and recommendations

Further original research is absolutely indispensable, notably in the Mediterranean basin to assess climatic changes and their related health impacts (Hosking and Campbell-Lendrum 2012). Accomplishing this requires the establishment of a pan-Mediterranean research coordinating institution (Trans-Mediterranean CDCs) with ties to international funding organizations, stakeholders in the region and abroad, and established international and national scientific communities. The research groups involved in climate change and its impacts should be the promoters of this trans-regional programme that aims to train researchers to conduct longitudinal studies, in data acquisition and comparative analysis, and should guide research toward priority topics like observational studies, transdisciplinarity, analytical and epidemiological studies, and statistical analysis on spatio-temporal series of disease cases. They are few or no studies addressing important topics such as water supplies and waterborne diseases, food and malnutrition, and the health risks of extreme events other than the effects of heat (Hosking and Campbell-Lendrum 2012). In the same vein as that proposed by Negev et al. (2015), epidemiological data on major infectious diseases morbidity and mortality should be collected systematically, and consolidated with environmental, socio-economic, demographic and ecological data. Environmental management of infectious diseases like vector-borne diseases, which can require the elimination of breeding sites for mosquitoes through the use of insecticides, should be discussed regionally and weighed against pesticide toxicity through structured-decision making. Relevant examples could be adopted by other countries in the region. Ideally, health system preparedness for climate change-sensitive diseases should be evaluated regularly, specifically when environmental signals like the El Niňo phenomenon occur.

In the Mediterranean region where climate change may add to existing problems (drought, water scarcity, traffic, etc.), non-communicable diseases (NCDs) are strongly challenged by changes in the climate via both direct and indirect pathways (Cecchi et al. 2010). Climate change, and its driver greenhouse gas emissions, affect NCDs through: 1) an increased number of cardiorespiratory deaths and acute morbidity due to heatwaves; 2) increased frequency of cardiorespiratory events due to higher concentrations of ground level ozone; 3) changes in the frequency of NCDs due to transboundary long-range air pollution by particulate matter (e.g. related to fires and aerosols); 4) increased incidence of skin cancers due to excessive sun exposure of the skin; and 5) altered spatial and temporal distribution of allergens that increases the risk of allergic diseases. These pathways will not only affect patients with existing NCDs by causing their aggravation but may also influence the incidence and hence the prevalence of NCDs. People who are very young, old, poor, or who live in vulnerable areas are more fragile (McMichael et al. 2006). However, it is not easy to evaluate the impact of climate change and related factors on the prevalence, the severity and the incidence of NCDs. Research on the adverse impacts of climate change on NCDs should have the following goals: 1) Improve our understanding of the climate system and its drivers; 2) Improve our understanding of climate impacts and vulnerability; 3) Increase our understanding of adaptation pathways and their putative health costs; 4) Identify the mitigation options that reduce the risk of longer-term climate change; 5) Improve decision support and integrated assessment; 6) Link environmental, socioeconomic and health datasets through an exposomic approach that will provide new insights into the potential associations between climate change and human health and wellbeing.

These goals have to be based on cross-cutting research capacities: 1) Integrate medicine, toxicology, natural and social science, engineering, and other disciplinary approaches; 2) Ensure availability of observations, monitoring, and infrastructure for critical data collection and analysis; 3) Build capacity for climate assessment through education, training, and workforce development; 4) Enhance the development and use of scenarios; and 5) Promote international research and collaboration. These capacities are achievable in the Mediterranean region where important resources and competences exist.

Regarding training, researchers, medical doctors and public health epidemiologists should be trained to climate change risks and to long-term understanding of processes at work in human health outcomes, and not solely to short-term, molecular-based approaches. Public education and communication is essential and should be strengthened in the Mediterranean region with public involvement in prevention of outbreaks and in combating infectious disease foci like breeding sites for mosquitoes (Negev et al. 2015). Evaluation and assessment of the implementation of adaptation plans to climate change and health should be conducted according to structured-decision making and sustainable practices, and the French example of climate change and health assessment (Guégan and Pocher 2010) is a start in this direction. The Mediterranean should benefit from adopting an ecosystemic approach, the so-called OneHealth-EcoHealth concepts, to reach the sustainable development goals, and at least numbers 3 (good health and human well-being) and 13 (climate action). Health and well-being in the Mediterranean, whatever the borders and the sub-regions should be the unifying theme that enables crystallization of a trans-national initiative such as the Mediterranean Union. We also would like to stress the assets of the Mediterranean region with regard to health outcomes. Indeed, the Mediterranean diet displays a number of health benefits compared to other diets and it should be preserved at least to partially offset some of the detrimental effects that climate change may have. As previously mentioned another asset in the Mediterranean region is the wide range of skills and facilities that already exist. An integrative public health approach with investments in regional public health infrastructures should be applied here.



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Part 3

# Adaptation, resilience, conservation of resources and prevention of risk

< © IRD/G.Michon – Local knowledge can represent a powerful tool in managing the vulnerable Mediterranean highlands. High Atlas, Morocco, 2015.

Chapter 1

# Societies and climate change in the Mediterranean

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## Abstract

We may not have fully realized yet the full importance of climate change as a social issue in the Mediterranean region. Many studies are available to policy makers and to the public. They show how changes in climate parameters may drive deep societal transformation around the Mediterranean and should impact agricultural production, provision of ecosystem services, risk exposure to extreme weather events, or human and animal health. The chapters collected in this section hence offer particularly interesting insights into how climate change is a crucial driving force for the whole economic, political, and social structure in the region.

Sub-chapter 3.1.1 reveals how changes in the law, in three different North African contexts, take climate-related issues into account. The authors emphasize how fighting climate change or implementing adaptation measures cannot be done without setting legal policy frameworks. The best research and innovation ideas cannot be implemented without a robust legal system. Without clear and

ambitious climate acts, public action for climate will not resist the various counter-strategies elaborated by social actors; ambitious measures for sustainable development will thus be impeded or delayed. From this point of view, sub-chapter 3.1.1 is an interesting overview of the heterogeneous approaches of Maghreb countries in defining and implementing climate targets in their juridical framework.

Sub-chapter 3.1.2 deals with the massive issue of human migration. The Mediterranean is both a border and a crossing point between two highly contrasting regions – both economically and socially. It is a place where, for several years, we have observed the tragedy of migrants seeking to reach the shores of the European Union. Among the multiple causes and driving forces of these South-North migrations, climate change plays a key role that research can help us better understand. Sub-chapter 3.1.2 reveals the urgency of the need for a conceptual and methodological clarification for the analysis of migration and its links with the socio-environmental crisis. It demonstrates how challenging and necessary it is to conduct integrated research on socio-ecosystem dynamics on multiple scales, and particularly at macro-regional level.

Urban systems are, in this respect, particularly interesting socio-environmental objects in terms of adaptation to climate change (sub-chapter 3.1.3). The southern shore of the Mediterranean is engaged in deep urban transition, just as the North Shore was a few decades ago. This has resulted in huge demographic changes which increase the size and the population of coastal urban areas. Research, again, leads to a better understanding of the characteristics and complexities of urban climate change and its consequences. Modelling is a necessary tool if effective and fair public policies are to be created in future. Climate change will require more integrated urban management. Sustainable urban development needs to coadoptnduct integrated policies instead of dealing separately with, for instance, waste management, energy issues, transportation, river management, housing policies, and social integration – all elements of the same extraordinarily complex jigsaw puzzle. Assembling all its pieces will require a joint effort by scientists, public decision makers, and civil society.

## Résumé

Le changement climatique en région méditerranéenne est un enjeu de société dont nous n'avons peut-être pas encore pris toute la mesure. De nombreux travaux existent pour attirer l'attention des décideurs publics et de l'opinion sur les risques qu'une modification des paramètres climatiques comporte pour les sociétés du pourtour méditerranéen au plan de la production agricole et de la fourniture des services écosystémiques, de l'exposition aux risques liés aux phénomènes climatiques extrêmes ou aux maladies émergentes. Les textes réunis

dans cette section permettent de voir mieux encore comment le changement climatique est une force qui travaille l'ensemble de la structure économique, politique et sociale.

Le sous-chapitre 3.1.1, en faisant un point sur la manière dont le droit, dans trois contextes différents au Maghreb, prend en compte les enjeux liés au climat rappelle de manière très claire que lutter contre le changement climatique ou mettre en place des mesures pour s'y adapter ne peut se faire sans cadres juridiques pour l'action publique. Les meilleures idées issues de la recherche et de l'innovation doivent pour prendre corps pouvoir s'appuyer sur un appareil juridique qui les rend possibles. En l'absence de cadres juridiques clairs et ambitieux, l'action publique en faveur du climat ne peut trouver sa place au sein de l'ensemble des stratégies portées par les acteurs sociaux et ne peut engager les sociétés et les économies sur la voie d'un développement soutenable. De ce point de vue, le sous-chapitre 3.1.1 est très éclairant sur la diversité des situations au Maghreb en matière de définition et de mise en œuvre d'objectifs pour le climat dans le droit de l'environnement.

Le sous-chapitre 3.1.2 est consacré à l'immense question des migrations. La Méditerranée, frontière et point de passage entre des ensembles régionaux très contrastés au plan économique et social, est le lieu où depuis plusieurs années s'observe la tragédie des migrants cherchant à rejoindre les rivages de l'Union européenne. Parmi les moteurs de ces migrations du Sud vers le Nord, le changement climatique joue un rôle que la recherche devra s'attacher à encore mieux comprendre dans le futur. Le sous-chapitre 3.1.2 introduit à ce travail de nécessaire clarification conceptuelle et méthodologique dans l'analyse des flux migratoires en relation avec les crises socio-environnementales. Il montre tout l'enjeu qu'il y a à mener des travaux intégrés sur les dynamiques des socio-écosystèmes à plusieurs échelles et particulièrement à l'échelle macro-régionale.

Les systèmes urbains sont de ce point de vue des objets socio-environnementaux particulièrement importants pour les défis du changement climatique (sous-chapitre 3.1.3). La rive sud de la Méditerranée est engagée dans une transition urbaine, comme la rive nord l'a été quelques décennies auparavant, dans un contexte démographique dynamique qui a pour résultat de produire des ensembles urbains de plus en plus étendus et qui concentrent des populations de plus en plus nombreuses. La recherche permet de mieux en mieux comprendre les caractéristiques du climat urbains, à échelle locale. La modélisation est un outil nécessaire dans l'optique de l'établissement de politiques publiques efficaces et justes. Le changement climatique rendra nécessaire une gestion des villes plus intégrée car, dans la visée d'un développement soutenable, il conviendra de considérer, par exemple, la gestion des déchets, la question énergétique, les transports, l'aménagement des cours d'eau, les règles et principes d'urbanisme, l'intégration sociale comme des éléments du même puzzle. Ce puzzle est d'une extraordinaire complexité. Pour en assembler les pièces, il faudra un effort conjoint des scientifiques, des acteurs publics et de la société civile.

# When law addresses the environment

## A matter of principle or a deep-seated concern?

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## Introduction

In the wake of their recent political and social transformation, the three central Maghreb countries have adopted constitutions and legislations that address new and emerging questions and give greater focus to issues that had previously been dealt with on a minor level only. These issues include the environment, an urgent matter on a regional and global level and a theme that the law has seized upon for various reasons, taking account of ecological imperatives but other factors too. Questions of symbolism, respectability, international pressure and even fashionable thinking have pushed the Maghrebin states to reform their constitutions and laws to account for human rights, the rule of law, regionalization, environmental protection and natural resources as well as multiculturalism. Our chapter will take a brief look at the recent constitutional and legal reforms in Morocco, Algeria and Tunisia to see the place these concerns occupy, the type of solutions delivered and their feasibility, and how they dovetail with the challenge of reforms of the law and by the law, their scope and their limits.



# Morocco

Morocco is strongly affected by climate change due to its geographic location. The average increase in temperature across the country is estimated at 1°C, combined with significantly lower rainfall (a drop of between 3% and 30% depending on region), extreme events (e.g. droughts and floods), more frequent heatwaves and fewer cold spells, rising sea levels, phenomena all witnessed over the past few decades. Climate forecasts point to a gradual rise in aridity across the country, related to lower rainfall and higher temperatures, with these events occurring increasingly frequently after 2050.

## Public policies

An endogenous development policy giving key focus to the availability of water resources has long been implemented. As the world mobilizes to tackle climate change, Moroccan leaders are rightfully upholding the policy of dams promoted by the late King Hassan II for more than half a century.

Morocco has therefore long been aware of and preparing for climate issues and, against this background, has taken a proactive political approach on the international stage. After the 1992 Rio Summit, the Kingdom made a renewed commitment to reform with a concern for sustainable development and environmental protection. In fact, the monarch took every opportunity to speak about the need for sustainable development. For example, during the national debate on the drafting of a Charter for the Environment in 2010, the King emphasized the importance of incorporating the environment into government action and the need to drive the sustainable development process, making sure ecology plays a central role. The Charter is devised as the basis for “green growth and the new economy, opening up vast perspectives for the emergence of innovative activities likely to create jobs”.

Morocco ratified the UNFCCC in 1995. It hosted COP7 in 2001. In 2009, the Moroccan government presented the “National Climate Change Action Plan”. In June 2015, a national conference was held, under the high patronage of the King of Morocco and the chairmanship of the head of government, to present Morocco’s contribution to the action against climate change. On the fringes of this conference, an agreement to recover household waste for power generation was signed with the cement industry’s professional association. In September

2015, King Mohammed VI and French President François Hollande signed the Tangiers Call, a joint declaration for "strong action and solidarity for the climate". The Tangiers Call comes after the Manila Call and the Fort-de-France Call.

An Environment Ministry has also been created, headed by Mrs. Hakima El Haite, doctor in environmental science. She took part in negotiations at the Warsaw (COP19, 2013) and Lima (COP20, 2014) conferences. In the wake of COP21, the Environment Minister was appointed "Climate Champion" for Morocco. She is also a member of the COP22 steering committee. Nonetheless, environment and climate policies are not reserved to a single ministry. They are cross-cutting issues involving various ministries and authorities including the High Commission for Water and Forests and the Fight against Desertification, and the National Electricity and Drinking Water Authority (ONEE). The Moroccan government's policy on climate was set out in a document published my Mrs. El Haite's ministry in 2014[1]. Within the framework of the United Nations Framework Convention on Climate Change, Morocco regularly reports to the United Nations. Its latest report was produced in January 2016[2]. It refers to the drafting of a National Low Carbon Development Strategy and a National Climate Change Adaptation Plan in 2016.

Morocco has set up a coordination tool known as the PCCM (Moroccan Climate Change Policy). The PCCM encompasses various programs and strategies implemented to tackle climate issues, on the basis of which a "National Vision" has been drawn up, combined with a National Adaptation Plan (NAP) to identify priority actions in response to urgent and immediate CC adaptation requirements.

Replacing the term "climate change" with the slogan "climate chance", Morocco volunteered to host COP22 in Marrakech in 2016. At the opening session of COP21, King Mohamed VI declared that holding COP22 in Morocco is an opportunity to put the spotlight on Africa "where our planet's fate will be decided". At the same time, the King called for the consolidation of a comprehensive, operational, balanced and universal legal instrument to restrict global warming. Morocco defends an international climate policy with "common but differentiated, historical responsibilities". It endeavors to promote South-South cooperation on climate issues, most notably with the foundation of a climate change skills center, a structure with African, Arabic and Islamic offshoots.

As a sign of its willingness, Morocco was the first Arabic country – and one of the first countries in the world – to submit its Intended Nationally Determined Contribution, i.e. its national mitigation target on greenhouse gas emissions. It

1. The climate change policy. Ministry reporting to the Minister for Energy, Mines, Water and Environment. March 2014 (document in French). http://www.environnement.gov.ma/PDFs/politique_du_changement_climatique_au_maroc.pdf

2. The report or the Third National Communication to the United Nations Framework Convention on Climate Change, January 2016 (document in French). Ministry reporting to the Minister for Energy, Mines, Water and Environment. http://www.yabiladi.com/img/assets/TCN_web.pdf

has undertaken to reduce its emissions by 13% by 2030 and would eventually like to achieve a 32% fall with international financial backing, most notably the Green Climate Fund.

Salaheddine Mezouar, the Minister for Foreign Affairs and chair of the COP22 steering committee, presented the Moroccan 2020 action, which focuses on three areas: pushing for climate finance, adapting African agriculture to climate change, and maintaining protective measures against desertification.

In turn, Moroccan civil society has begun to tackle climate issues, taking a critical approach to the State's policy. A Moroccan Alliance for Climate and Sustainable Development (AMCDD) was founded in May 2015. It brings together Moroccan associations and networks active in the fields of climate change and sustainable development. In July, with backing from the MFP/UNDP and the EU, it organized a workshop to analyze and discuss the drafting and implementation of Morocco's public policies and international commitments to tackle climate change. The workshop pointed to the limited integration of Morocco's climate change policy in public policy and most sector plans. ATTAC Morocco criticized the "illusory commitments" made at COP21[3].

Finally, Morocco has entered top 10 in the Climate Change Performance Index introduced by Climate Action Network Europe and Germanwatch, moving up from 15th place in 2014 to ninth in 2015.

## Constitutional and legal measures

Morocco's legal development reflects the significant focus placed on the environment and sustainable development. There has been a shift away from one-off measures applied in response to endogenous economic growth or sector-related management issues, towards a policy of integration into the international framework promoting sustainable development and action against climate change. This process is reflected in the latest Constitution, drafted in 2011, where the notion of sustainable development is enshrined[4]. An economic, social and environmental council was established by the new Constitution.

In 1995, Morocco signed and ratified the main international conventions applicable to the environment, including the Convention on Biological Diversity (CBD), the United Nations Convention to Combat Desertification and the United Nations Framework Convention on Climate Change.

From a legislative viewpoint, a framework law (Loi-cadre no. 99-12 in 2014) was adopted, serving as a national charter on the environment and sustainable development. The national sustainable development strategy was drafted on the basis of the measures set out in this framework law. A comprehensive legal

3. Attac Morocco. Report on Climate Justice in Morocco (in French). http://cadtm.org/IMG/pdf/Attac_Rapport_Justice_climatique_FR.pdf

4. :"{…} It {the State} works towards achieving sustainable, human development, able to ensure the consolidation of social justice and the conservation of national natural resources and the rights of future generations."

package on environmental protection has been adopted (most notably law no. 10–95 on water promulgated by Dahir no. 1–95–154 dated 16 August 1995; law no. 11-03 (2003) concerning the protection and promotion of the environment; law no. 12-03 (2003) concerning impact studies; law no. 13-03 (2003) on action against air pollution; law no. 28-00 (2006) concerning waste management and disposal; law no. 57-09 (2010) on the creation of the Moroccan Agency for Solar Energy; law no. 22-07 (2010) on protected areas; law no. 22-10 (2010) on the use of degradable and biodegradable plastic bags and sachets; law no. 16-09 (2010) to turn the Centre for the Development of Renewable Energy (CDER) into the National Agency for the Development of Renewable Energy (ADEREE); law no. 13-09 (2011) on renewable energies; law no. 47-09 (2011) on energy efficiency; law no. 58-15 (2015) amending and supplementing law no. 13-09 (2015) on renewable energies; law no. 81-12 on coasts).

The existing institutional framework was inadequate and unconducive to the coordination and arbitration of public policies. It became apparent that there was a need for cross-cutting measures involving all sectors concerned if climate policy was to be implemented. The national vision promoted by Morocco most notably aims to strengthen the institutional mechanisms stemming from the Framework Law on the Environment and Sustainable Development, which defines the institutional structures, their roles, specific tasks, composition and resources.

## Algeria

Let us provide a few figures, which are more eloquent than any analysis of the scale of the ecological catastrophe in Algeria: 43% of the Algerian population lives in a 50-km-wide, 1,200-km-long strip, with a population density of 281 people per square kilometer (versus a national figure of 12 per square kilometer), where 5,242 industrial units are also located (i.e. 51% of the national total); 1,053,907 $m^3$ of mixed wastewater is discharged daily in the 11 main ports, 12,000 metric tons/year of oil is discharged by large cargo vessels and only 5% of waste is recycled; more than 8,684 metric tons of solid urban waste is sent to 380 uncontrolled landfills located along the coastal strip, while an increase in illegal extraction is leading to the retreat of sandy coastlines; utilized agricultural area (UAA) is shrinking dramatically (it stands at 0.007 ha/inhabitant in coastal communities).

This is a pretty bleak picture. So what can the law do about it? Amendments to Algeria's legal framework covering environmental protection have been made within a general context of legal insecurity brought about by repeated changes to the systems and models of governance.

## National and international instruments

Algeria has ratified the following international instruments: the African Convention on the Conservation of Nature and Natural Resources of 16 September 1968 in Alger[5]; the Convention on Wetlands of February 1971 in Ramsar (Iran)[6]; the 1972 Paris Convention concerning the Protection of the World Cultural and Natural Heritage[7]; the Convention on International Trade in Endangered Species of Wild Fauna and Flora, signed in Washington on 3 March 1973[8]; the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal of 22 March 1989; the Vienna Convention for the Protection of the Ozone Layer of 22 March 1985 and the Montreal Protocol on Substances that Deplete the Ozone Layer, agreed on 16 September 1987; the United Nations Framework Convention on Climate Change of 9 May 1992 in New York and the United Nations Convention on Biological Diversity agreed on 5 June 1992 in Rio de Janeiro; the United Nations Convention to Combat Desertification adopted in Paris on 17 March 1994. In addition to these conventions, the country has also signed up to: the Dublin Statement on Water in 1992; the Stockholm Statement; the United Nations Conference on Environment and Development held in Rio de Janeiro on 13 June 1992 (Rio Declaration and Agenda); and the 2002 World Summit on Sustainable Development in Johannesburg.

At COP21 in Paris in 2015, Algeria committed to a 7% unconditional cut in greenhouse gas emissions (rising to 22% with international financial aid and assistance and international technology transfers). A National Climate Committee – with close involvement of the CNES (National Economic and Social Council) – has also been set up to monitor, coordinate and assess these issues.

However, it is not enough to simply ratify treaties: they also have to be incorporated into national law or enforced (by judges in particular) in virtue of the principle of primacy of international treaties over domestic law. The real picture is far less attractive as no one has been bold enough to submit a legal claim calling for the international agreements ratified by Algeria to be applied, and the courts also refuse to comply.

We need to look beyond the hierarchy of laws to determine the prevalence of environmental concerns. The latest version of the Algerian Constitution (dating from 2016) includes two measures: Article 17 *bis* stipulates that “the State guarantees the rational use of natural resources and their conservation for the benefit of future generations. The State protects agricultural land. The State also

5. Decree no. 82–440 of 11 December 1982 ratifying the African Convention on the Conservation of Nature and Natural Resources, signed in Alger on 15 September 1968. JORA (official journal) No. 51 of 11 December 1982, Page 1685

6. Decree no. 82–439 of 11 December 1982 concerning Algeria's adoption of the Convention on Wetlands, of international importance, especially as a wildfowl habitat, signed in Ramsar (Iran) on 2 February 1971,

7. Order no. 73-38 of 25 July 1973 ratifying the UNESCO Convention concerning the Protection of the World Cultural and Natural Heritage.

8. Decree no. 82–498 of 25 December 1982 on Algeria's adoption of the Washington Convention on International Trade in Endangered Species of Wild Fauna and Flora dated 3 March 1973.

protects public water resources." Article 54 *ter* states that "Citizens have a right to a healthy environment. The State works to protect the environment. The law defines the obligations of individuals and legal entities with regard to environmental protection."

The environment is enshrined in the positive legal system in four main laws: (i) Law 83-03 of 5 May 1983 on environmental protection[9] testifies against the preceding socialist era of polluting industries. It makes the conservation, defense and improvement of the environment a public interest issue. It states that nature, habitats and the environment are to be protected against hazardous activities; (ii) Law 01-19 of 12 December 2001 on waste management, control and disposal,[10] which recommends the development of waste recovery, treatment, disposal and management activities; (iii) Law 02-02 of 5 February 2001 on the protection and promotion of the coastline. It organizes coastal use and management (land use planning); (iv) Law 03-10 of 19 July 2003 on environmental protection within the context of sustainable development. Its authors set out the following principles: conservation of biological diversity, prevention of damage to natural resources, substitution, integration, prevention and repair of environmental damage caused by the priority source, precaution, polluter pays, motivation, information and participation.

## Mechanisms and institutions

We can now look at the mechanisms and institutions tasked with making sure this legal package is effective. There are three techniques: planning, impact studies and tax incentives. The polluter-pays principle is implied in the 1992 budget act, which introduced a tax on polluting or environmentally hazardous activities[11]. It is stated more explicitly in Article 3 as one of the basic tenets of the 2003 law, and defined as a principle "whereby any person whose activities cause or are likely to cause environmental damage shall bear the costs of all measures required to prevent or mitigate pollution or to clean up the site and its environment."

Various institutions are charged with protecting the environment; at government-level, the administration has undergone a series of changes: from the time of establishment of the first environment-related body in 1974 (the National Environment Board) to the creation of a Secretariat of State for the Environment in 1996, the service has reported to various departments, namely the Water department in 1984, Research and Technology in 1988, Education and Higher Education in 1993, and the Ministry of the Interior, Local Authorities and Administrative Reform in 1994. The Secretariat of State for the Environment founded in 1996 only survived three years until 1999 when its prerogatives were

9. Official Journal no. 6 dated 8 February 1983, p. 380.

10. Official Journal no. 77 dated 15 December 2001

11. Article 117 of law no.91/25 dated 18 December 1992 concerning the 1992 budget act, JORA (official journal) no. 65, dated 18 December 1991.

transferred to the Ministry for Public Works, Land Use Planning, the Environment and Urban Affairs. Finally, a Ministry for Land Use Planning and the Environment was set up in 2001.

The issue of environmental protection has been partially decentralized, with responsibility incumbent upon communities and the *wilaya*. Order no. 67-24 of 18 January 1967 concerning the communal code, as amended and supplemented by law 81-09 of 4 July 1981, invites the people's communal assembly to "take part in all efforts aimed at protecting the environment and to work towards its improvement across the community's territory" and at "improving of the quality of life and efforts to reduce pollution" (Art. 136). In law 90-08 of 7 April 1990 concerning communities, subsequently supplemented, Article 92 permits the people's communal assembly to carry out prior checks into all projects incurring environmental risks. Law no. 11-10 of 22 June 2011 concerning communities states that "the implementation of any investment and/or infrastructure project or any project that is part of a sector program for development of the community's territory shall require approval by the people's communal assembly, particularly with regard to the safeguarding of agricultural land and impacts on the environment" (Article 109). Concerning the *wilaya*, Article 33 of law 12-07 of 21 February 2012 provides for a permanent commission responsible for "health, hygiene and environmental protection".

In addition, there is an array of administrative structures serving the environmental cause, in the form of observatories, centers and agencies. Algeria has two observatories involved in environmental matters: the National Observatory on the Environment and Sustainable Development, and the National Observatory on the Promotion of Renewable Energies. It also has two centers, the National Centre for Cleaner Production Technologies[12] and the Centre or the Development of Biological Resources[13]. Finally, there are four agencies[14], the National Agency for Nature Conservation, the National Waste Agency, the National Earth Sciences Agency, and the National Climate Change Agency.

There are three dimensions to the green economy: firstly, green or sustainable entrepreneuring; secondly, sustainable consumer habits and production methods; and finally, corporate social responsibility. Recent studies point to extraordinary entrepreneurial potential because 99% of the energy used is from finite, fossil sources causing pollution and requiring subsidies. 40% of that energy is for household use. It causes significant environmental damage (discharge and storage of hazardous chemical waste). As concerns the second aspect, sustainable consumer habits and production methods, let us take the example of the plastic bag. It is firmly embedded in Algerian society: the average person uses 200 every year. The

12. Executive decree no. 02-262 of 17 August 2002 concerning the creation of the National Centre for Cleaner Production Technologies.

13. Executive decree no. 02-371 of 6 Ramadhan 1423 (11 November 2002) concerning the creation, organisation and operations of a Centre for the Development of Biological Resources, JORA (official journal) no. 74 of 13 November 2002, pp. 6–9.

14. Executive decree no. 91-33 of 9 February 1991 concerning the reorganisation of the National Museum for Nature to create a National Agency for Nature Conservation.

country's total consumption is estimated at 7.7 billion units a year. Old habits die hard, despite the alarm signals being rung across the world to warn of how dangerous this type of packaging is for public health and the environment. As for corporate social responsibility, ISO standard 26000 describes this as "the responsibility of an organization for the impacts of its decisions and activities on society and the environment, through transparent and ethical behavior that contributes to sustainable development, including health and the welfare of society." Seventeen public and private companies have introduced ISO 26000 on social responsibility and innovation. A pool of 14 national experts has been formed while 17 voluntary organizations have signed up to implement the principles of social responsibility, compliant with the terms of the standard and as part of the CR MENA (social responsibility for the Middle East and North Africa) project.

## Tunisia

Under the presidency of Zine el Abidine Ben Ali (1987–2011), environmental protection appeared to be one of the flagship issues in public policy. It came within the protective scope of the authoritarian state and, in the urban environment, was symbolized by the green and flower-decked boulevards that crisscross most Tunisian towns. As part of a highly controlled step towards political openness, the authorities accepted the legalization of a small ecology party, the Green Party for Progress, in 2006. From 1991 onwards, public policy resulted in the creation of a fully-fledged Ministry of the Environment (and Sustainable Development as of 2005). The ministerial structure has twice been downgraded to the status of secretariat of state, first in 2002–2003 when current prime minister Habib Essid, was minister, then again after the revolution, from January 2014 to February 2015, headed by Mounir Mahjdoub under Mehdi Jomaâ's interim government. The present minister is Nejib Derouiche.

In 1993, compliant with the recommendations of the 1992 Rio Summit, a National Sustainable Development Commission was founded to coordinate the various stakeholders in environmental policy. In addition, the government was supported by a number of agencies, first and foremost the Environmental Protection Agency (ANPE), founded by law on 2 August 1988, then the Coastal Protection and Development Agency (APAL) in 1995, the Tunisian Waste Management Agency (ANGED) in 2005, and other public establishments such as the National Sewerage Board (ONAS), founded in 1974 and restructured in 1993, and the Tunisian International Environment Technology Centre (CITET), opened in 1996. There are several agencies involved in environmental policy that report to other ministries, including the National Energy Management Agency (ANME), under the Ministry of Industry, and the Urban Rehabilitation and Renovation Agency (ARRU), under the Ministry of Infrastructure.

In addition to this denser institutional network, environment law has been strengthened via a series of legislative and regulatory measures – the law of 17 July 1995 on water and soil conservation; the law of 10 June 1996 concerning waste management and disposal; the law of 4 June 2007 on air quality – often following on from the international conventions ratified by Tunisia.

On the basis of this framework, judges are able to make a judicial contribution to the drafting of environmental law in Tunisia. [15] However, although the government in place promoted environmental protection, it failed to implement the two actions required to bring environmental law into being: its constitutional enshrinement, necessary despite the numerous overhauls of the constitution under the presidency of Ben Ali, and its codification with the drafting of an environment code.

## Constitutionalization

The constitutionalization of environmental protection finally began with the law dated 16 December 2011 on the provisional organization of public powers, serving as a "temporary constitution" during the interim period. Its Article 6 stipulates that the basic principles on the environment and land use planning, together with the basic tenets of energy management, are a matter for law. However, environmental protection was enshrined in the constitution in a much more remarkable way on 27 January 2014. The preamble to the Constitution states the need to contribute "to the preservation of a healthy environment that guarantees the sustainability of our natural resources and bequeathing a secure life to future generations". Article 12, included in the section on general principles, declares that "The state shall seek to achieve social justice, sustainable development and balance between regions based on development indicators and the principle of positive discrimination. The state shall seek to exploit natural resources in the most efficient way." Special focus in put on *natural resource management* in Article 13: "Natural resources belong to the Tunisian people. The state exercises sovereignty over them in the name of the people. Investment contracts related to these resources shall be presented to the competent committee in the Assembly of the Representatives of the People. The agreements concluded shall be submitted to the Assembly for approval."

With regard to this sensitive issue that has led to several political mobilizations over recent years, the Constitution provides for parliamentary monitoring of the executive's decisions, and for the mechanisms enabling redistribution of income at national level (Article 136).

All citizens have the right to a "healthy and balanced" environment, which entails an obligation for the State, according to Article 45 in the section on rights and freedoms: "The State guarantees the right to a healthy and balanced

15. See the Administrative Tribunal of Tunisia's document, *Les sources du droit de l'environnement en Tunisie*, Cartagena conference, 2013 report from Tunisia (in French), http://www.aihja.org/images/users/114/files/Congres_de_Carthagene_-_Rapport_de_la_Tunisie_2013-TUNISIE-FR.pdf.

environment and the right to participate in the protection of the climate. The State shall provide the necessary means to eradicate pollution of the environment." A broad interpretation of this obligation justifies Tunisia's contribution to action against climate change via the United Nations Framework Convention on Climate Change. This right is clearly exercised when it comes to water (article 44)**: "**The right to water shall be guaranteed. The conservation and rational use of water is a duty of the state and of society."

Finally, the Constitution confers an intrinsic guarantee on environmental protection, with the creation of an independent constitutional body, the Commission for Sustainable Development and the Rights of Future Generations (Part Four, Article 129)[16].

## Deteriorating environmental conditions and inadequate legal framework

In the long institutional transitional period experienced by Tunisia since the fall of President Bel Ali, the constitutional enshrinement of environmental protection has not prevented the ongoing deterioration of environmental conditions. "The environment is the first victim of the revolution," believes ecologist militant Abdelmajid Dabbar[17]. This divergence has been maligned in the press, which has highlighted issues with high visibility such as waste collection. It has given rise to a far-reaching critical approach from civil society organizations, for example at the social environment forum held in Monastir from 6 to 8 February, ahead of the World Social Forum. Most notably, participants called for the development of special laws on the environment and the definition of an environment code.

When it comes to environmental protection, one of the main tasks for the public sector is waste collection and treatment[18]. Yet this job is primarily delegated to local authorities, which have been thrown into chaos since the revolution. Municipalities have been dissolved and replaced by special delegations, which are not elected and are therefore of questionable legitimacy[19]. They have insufficient human resources and there have been long strikes in the cities. Financial resources are all the more limited since taxes (especially housing tax) are not being collected. Catastrophic images of the consequences of the authorities' incompetence in the area of waste collection means that the debate has been entirely focused on this question.

16. This body was omitted in the text of the penultimate draft constitution in April 2013. It was reintroduced after strong protests from ecological groups and the Network for Nature and Development in Tunisia (RANDET), and the group known as Eco-Constitution Alternative.

17. It should be noted that the green parties did not make much headway in the revolutionary context. The main party, Tunisie Verte, founded in 2004 but not recognised under the previous regime, became part of the *Front Populaire* for a time (left-wing alliance) but split from it in 2014. The green parties are conspicuously absent at presidential and legislative elections.

18. For a comprehensive analysis of the waste collection and treatment issue, see Lilia Blaise for Inkyfada (in French), *Poubelles, les points noirs de la Tunisie*, https://inkyfada.com/2014/08/enquete-dechets-tunisie-partie1-poubelles-points-noirs-infographies/.

19. Electoral legislation for municipal elections is still under review by parliament.

State institutions are not running as smoothly as they should be either. This affects communication campaigns and the statistical analysis and control of types of pollution that are less visible than waste but just as dangerous[20]. Since the revolution, many areas have been taken on-board, including wastewater and drinking water quality, the conservation of forests, action against urban air pollution, and so on.[21] Yet the different authorities do not communicate and agencies no longer publish annual reports, meaning environmental policy is increasingly unintelligible. Another issue is the monitoring of Tunisia's application of the international conventions it has signed concerning the environment[22].

Since 2011, there has been little room for environmental issues on the agenda of the legislative bodies – the national constituent assembly then the Assembly of the Representatives of the People – as the program has been dictated by the constitutional and electoral calendar. The constitutional debate may have raised a number of environmental issues, as mentioned above, but discussions have remained consensual across the political spectrum. They were only dealt with from a legislative angle with regard to another priority, the country's security situation, when the ARP adopted the organic law dated 7 August 2015 on the fight against terrorism and money laundering. Article 13 of that law includes the following in the list of terrorist actions: actions that "impact food security and the environment, upset the balance of the ecosystem or natural resources, or endanger the population's lives or health"; "intentionally opening flood control barriers or spilling toxic chemical or biological products into dams or water facilities with the intent of harming the population". As for the drafting of an environment code, no date has yet been set. An initial diagnosis was conducted in 2013 within the framework of international cooperation (Tunisian-German environment program).

## Conclusion

An examination of the constitutional and legal texts and the institutional adaptations required for implementation in the three Maghreb states reveals a

20. On this subject, see: Yassine Bellamine, *L'écologie en Tunisie, entre absence de considération et défi structurel*, http://nawaat.org/portail/2014/04/25/lecologie-en-tunisie-entre-absence-de-considerations-et-defis-structurels/ (article in French). On the question of excessive media coverage of household waste disposal (also in French): Habib Ayeb, *L'écologie en Tunisie entre environnementalisme de mode postrévolutionnaire et urgences environnementales et sociales*, http://www.huffpostmaghreb.com/habib-ayeb/lecologie-en-tunisie-entr_b_9304348.html.

21. With regard to these issues, see the 2016 report from the Tunisian Observatory on the Environment and Sustainable Development and the related coverage in the Tunisian press on 8 June 2016. The Observatory was founded in 1995 and integrated the National Environmental Protection Agency in 2000.

22. This is true of the Stockholm Convention on Persistent Organic Pollutants, for which Tunisia embarked upon a process of revising and updating its implementation plan, with financial support from various international organisations.

general context of legal voluntarism but also its limits. In all three countries, we witness the emergence of concerns for the environment resulting in the introduction of a far-reaching legislative package, with the danger of falling into the trap of what the Egyptians call *al-hall bi-l-tashri‘* or “legislative opportunism”. In other words, every time an environmental issue arises, the law-makers are called on to put forward a solution with a new piece of legislation. Such legislative opportunism tends to neglect one important principle: thrift with words, with a subsequent impact on the effectiveness of the law. This trend is not specific to the Maghreb states and their environmental law. In fact, the law-making machine is a key characteristic of modern states. Nonetheless, when it comes to the environment, there is a huge gap between the content of an all-encompassing law and the actual conduct of individuals and businesses, who are frequently unfamiliar with that content. The outcome is that the law remains unheeded.

However, this trend towards legislative inflation brings about a considerable benefit for states at an international level. A country’s compliance with its international commitments is largely based on the drafting of texts showing that they have transposed the rules set out in the conventions into its own laws. In this respect, it does not matter whether or not the law is applied properly or at all: the signatory State’s willingness has been established and, with it, the related benefits in terms of image, funding and geopolitical positioning. To sum up, the law fulfils a function but not necessarily the one expected. Environmental law is obviously not intended to be instrumentalized in this way. The same applies to human rights, democracy and the rule of law.

Nonetheless, environmental concerns have been enshrined in the legal and institutional mechanisms of the central Maghreb states for the long term. This can be seen in the three constitutions: citizens are entitled to expect a healthy environment and the State is required to protect it. While this may be something of a fad, there is more to it than that. Enshrining this kind of principle in the basic law means it may later be invoked before the courts, including the constitutional jurisdiction. We are aware that this kind of appeal is conditioned by the political context specific to each State and, of course, involves sometimes huge economic implications. At the same time, this can trigger a virtuous circle – however small at first. If we take a skeptical stance and assume that the State wants to continue to benefit from its international environmental commitments, it cannot overtly oppose appeals for its own law to be upheld. It may be able to turn a blind eye to practices that fail to comply with its law, but it is more difficult for the State to disregard civil society’s appeals founded on the law that it has drafted and upholds, especially when those appeals are echoed beyond the strictly local context. If we take a kinder stance, we assume that the State is seriously committed to protecting and improving its citizens’ living conditions. This assumption is somewhat naive since there are numerous conflicts of interest in this domain, but it should not be immediately dismissed. The equation is quite simple: the more the State grants its population, the more consideration it gives to its quality of life.

# Human migration and climate change in the Mediterranean region

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The Mediterranean area is characterized by very high human mobility. In this region, labor migration has long been structured by colonial ties and economic development inequalities between the South and the North. Since the Second World War, and more recently following the Arab Spring movement, forced migration has become predominant. Today, the region is home to the highest refugee population in the world, displaced by protracted conflicts.

In addition, the Mediterranean region is particularly affected by climate change. Water as a resource is a matter of concern at various levels for all countries, in a region characterized by strong economic disparities, and where risk prevention policies are not equally implemented. Although the Southern part of the region – less developed in economic terms – is less responsible for global warming, those who live there are more exposed and more vulnerable to the risks associated with climate change. Multiple factors favor displacement (conflicts, economic inequality), and climate change can be considered as a booster of inequality which encourages migration.

Displacement related to environmental change and climate disasters is not a new phenomenon. Nevertheless, the potential for migration has greatly increased over the last decades due to the increasing concentration of population residing in areas designated as 'at risk', who suffer the consequences of climate change.

The effects of climate change are particularly felt in priority rural areas where the most vulnerable population lives.

However, the relationship between climate change and migration is not necessarily obvious. Nowadays, there is a broad consensus that climate change results in increased frequency and severity of disasters. Sudden and violent events such as floods, storms, landslides and other hydro-meteorological disasters have led to short-term or permanent population displacement. Climate change also produces slower upheavals such as the upsurge in droughts, soil degradation, desertification, salinization of freshwater resources, coastal erosion, river banks erosion and rising sea levels, leading to a gradual emigration. Ultimately, the consequences for food production, crop yields, fresh water supply, food prices, health and livelihoods are serious and affect the populations of entire regions. The issue of environmental and climate migration is therefore a key element in understanding current migration trends in the Mediterranean region.

## A recent focus on the relation between climate change and migration

Since the Rio summit in 1992, the international community has started a round of negotiations to address global warming and its effects. While the Intergovernmental Panel on Climate Change (IPCC), in its report published in 1990, warned the international community about the risks posed by climate change in terms of migration, the issue remained peripheral until 2010. Until then, migrants and internally displaced people were perceived by the international community as 'collateral damage' of climate change, without adressing the question of the causes of these movements. In 2010, during COP16, it was decided to encourage "measures to enhance understanding, coordination and cooperation with regard to displacement, migration and planned relocation induced by climate change"[1].

Since the mid-1990s, there has been a growing number of studies on migrants and the internally displaced due to climate change (Piguet & Pécoud, 2011; Gemenne, 2009; Cournil & Mayer, 2014). This new research agenda, combined with growing political demand on such a complex issue, has contributed to the renewal of the theoretical, methodological and legal framework. It is now acknowledged by most researchers that the decision to migrate or stay in situ is affected by a combination of socio-economic, historical, political and/or

1. United Nations Conference on climate change, Cancun - Mexico, 2010 (in French): http://unfccc.int/resource/docs/2010/cop16/fre/07a01.pdf

environmental factors. There is a continuum between different forms of migration and a combination of various determinants that shape migration movements. The two main difficulties lie in the complexity of determining and defining environmental migration accurately, and the in quantifying and assessing the specific role of climate change in the decision to migrate on a temporary or permanent basis.



## Climate refugees: a new category

Today, a multiplicity of concepts and categories are used to describe migration linked to environment and climate change. These populations are described as 'migrants', 'environmental refugees', 'climate refugees', 'displaced persons in relation with a natural disaster', 'ecological migration', etc. These are just some examples of the terms used to describe the same phenomenon. The frequency of the use of the term 'refugee' is not accidental. First, it suggests the idea of drama and emergency. Secondly, it assumes a legal protection, which, in this case still remains hypothetical. The use of this term goes back to 1985, when it was used as a report title for the United Nations Environment Programme (*UNEP*). More recently, another definition was proposed for 'climate refugees', defined "as people who have to leave their habitats, immediately or in the near future, because of sudden or gradual alterations in their natural environment related to at least one of three impacts of climate change: sea-level rise, extreme weather events, and drought and water scarcity " (Bierman & Boas, 2007). In both definitions, the use of the term 'climate refugees' seems to imply 'political refugees'. However, the association seems inappropriate. To date, 'climate refugee' is not a recognized legal status similar to 'refugee status' as defined by the 1951 Geneva Convention and the 1967 Protocol. In addition, none of the existing international instruments is likely to offer direct and sufficient legal protection to this population (Cournil & Mazzega, 2007).

In recent years, many statements have been published by scholars, experts and policy makers to advocate for a better care of this category of migrants. In line with these initiatives, an important step forward was taken at COP21, where a decision was adopted to: "develop recommendations for integrated approaches to avert, minimise and address displacement related to the adverse impacts of climate change".[2]

2. Article 8 of the Paris Agreement and Decision 1/CP.21 Paragraphs 48–52 (FCCC/CP/2015/L.9/Rev.1.)

## Difficulties in quantifying environmental migrants

While the legal definition of environmental migrants is still unclear, it is even more difficult to quantify this migration, which is diverse. Thus, some displacements are very limited in time, while others consist of repeated back and forth movements, some are internal displacements while others cross national borders. In 1995, an estimated 25 million people were displaced for environmental reasons. More recently, the report published in 2016 by the Internal Displacement Monitoring Centre and the Norwegian Refugee Council, based on different information sources, estimates that there were around 19 million people displaced by natural disasters, mainly related to meteorological phenomena. This figure does not include displacement resulting from the progressive effects of climate change, which remains hard to determine. Today, the Mediterranean region is exposed to this kind of long term effects, more than catastrophic events of great magnitude. It is thus impossible to determine how many individuals are currently displaced by the effects of climate change in the region. The report highlights the fact that most displacements are internal and 80% occur in Asia, knowing that Asia is home to 60% of the world's population.

## A population unequally affected by climate change in the Mediterranean region

The populations residing in the Southern part of the Mediterranean region are particularly affected by climate change. Access to natural resources is a key issue, and there is increasing pressure on water, soil, plant and animal resources. Climate change presents new challenges in terms of social and economic change and resilience. For example, droughts have always been a part of the history of Central Maghreb countries and water stress is a constant reality. These countries have often experienced periods of intense drought, of varying length. Drought is therefore a key element in explaining desertification and land degradation, and subsequently some migratory movements. Recurring almost cyclically, droughts often accompany famines, epidemics and movements of displacement and migration of populations. A study conducted by the Morrocan Ministry of Infrastructure, agriculture and the environment, shows that Morocco, 93% of whose territory is arid or semi-arid, has suffered eleven periods of widespread drought which intensity was moderate to high, and others less widespread but rather strongly felt. Moreover, there has been an acceleration of the frequency of drought, which has grown from one every ten years during the fifties and sixties, to two or even three per decade since. In 2008, the Moroccan government launched a program – the Green Morocco Plan Goals – designed to limit the impact of climatic hazards[3].

On the Southern and Eastern shores of the Mediterranean, where social inequality is high and poverty in rural areas is widespread, we can establish a link between climate change over the long term and internal migration. Maintaining a profitable agricultural economy is challenged by the lack of sufficient water resources. This progressive deterioration of the economic situation of entire agricultural regions reinforces social tensions over access to vital resources. Researchers have recently established a link between the long drought in Syria between 2007 and 2010 and the rural population displacement towards urban centers (Kelley et al. 2015). This has contributed to strengthening the socio-economic tensions in the peripheries of the most deprived Syrian cities. In the long term, environmental degradation – particularly related to access to water – can cause social tensions or even contribute to the development of armed conflicts (Kälin, 2010).

On the Northern shore of the Mediterranean Sea, the relationship between migration and climate change today is less easy to identify. Yet we are witnessing increasingly violent climatic phenomena with storms (in France, the flood of Vaison-la-Romaine in 1992) and landslides (in Italy, the Sarno landslide in 1998 or Cerzeto in 2005) which cause the local displacement of varying numbers of individuals. These events, however, did not give rise to any debate in these countries or result in the creation of a special status for IDPs (Guadagno, 2014).

# Conclusion

Today the effects of climate change in the Mediterranean region in terms of population displacement are difficult to identify. With the exception of certain powerful weather phenomena, but rather limited when compared to other regions of the world such as Asia, the effects of climate change fall in the long term. The main consequence is water resource scarcity, that has very important consequences in the agricultural sector. As a result, there is a development of internal migration towards poor urban peripheries increasing social tensions. In the longer term, this may contribute to increasing the number of international migrants, mainly towards European countries, because of the lack of local economic opportunities. The effects of climate change in the Mediterranean

3. The agricultural sector remains the largest of the Moroccan economy and a driving force of development: it occupies 40% of the active population, contributes nearly to 20% in the GDP and accounts for 40% of the value of exports.

region tend to strengthen regional inequalities. Displacement due to the effects of climate change may be linked today to other forms of migration – be they forced or economic – leading to more substantial international migration flows.



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# Observation systems and urban climate modelling

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Mediterranean cities are particularly vulnerable hot-spots of climate change in light of their spatial and geographical configurations (i.e. the proximity of the coastline, high water demand, a climate favouring summer drought and extreme meteorological events such as intense rains), and their continuous growth.

Understanding the interlinkage between spatial and temporal scales is crucial in climatology if we are also to understand phenomena occurring at urban scales. The simulations run with Regional Climate Models (RCMs) show, under various scenarios, the frequency and the intensity of extreme meteorological events such as summer drought, which could reinforce Urban Heat Islands (UHIs), and enable us to anticipate the future without nevertheless providing solutions at local scales. It is therefore beneficial and necessary to develop models, instruments and measurements capable of simulating local climate phenomena.

These local-scale approaches mark the first step towards adaptive methods for coping with climate change in the short and medium term. They could lead to the reconsideration of some urban policies (densification, land planning or energy policies), as well as architectural practices (orientation, use of materials). Planners will have to integrate the climate challenge within their practices and develop urban solutions in the Mediterranean to limit the negative effects of climate change (e.g. thermal discomfort, pollution), particularly in the summer period.



# Observations adapted to the urban complexity of Mediterranean cities

Specific measures are necessary in urban environments to spatialize meteorological parameters and therefore to compensate for the inadequacy of data recorded by conventional networks. However, at city scale, these measures require that particular consideration be given to the choice of measuring points and periods, and of instrument calibration. For instance, the UHI can be measured at three main altitude levels: surface, about 2 meters from the surface, and in the open air (Carrega, 2003).

## Types of measurement in cities: stationary and mobile air temperature

There are two types of measurement: stationary or mobile. In the first case, they are recorded under shelter within a network of meteorological sensors or stations (fig. 1) established for densifying a conventional network or for enabling climate observations at micro and local scales according to a given question: UHI, temporal and spatial variation of temperatures, *etc*. Precautions such as clearing of the environment, ventilation of the site throughout the day, and safety measures against power failure, vandalism and theft, must be taken when installing the equipment in cities.

The duration of mobile measurements should be limited (max. 30-50 min) to avoid bias due to temporal variation. Depending on the travel distance, journeys can be made by car, on foot or by bike (box 1). Measurements can be recorded continuously or discontinuously with stops of no more than two minutes per measurement point. It is important to note that this type of field survey requires considerable physical and material efforts.

## Application: measurement of the urban heat island in Sfax

The UHI is studied using mobile air temperature measurements (at 2 meters above ground and, whenever possible, a minimum distance of 5 meters from the buildings) that are recorded with portable sensors. These measurements, carried out in July 2012, were only recorded at night during radiative conditions: they reveal spatial thermal disparities between the diverse types of surface in the city and its surrounding countryside. The measurements, which were obtained

*Figure 1*
*Temperature and humidity monitoring systems under shelter during a summer period measurement campaign in Marseille. Briche, 2016.*

by three teams to ensure maximum coverage of the agglomeration, were conducted between 1 and 2am, with very light wind and fluid traffic.

A temperature difference of 4 to 7°C is observed (fig. 4) between the city centre – the medina – and the surrounding countryside (a large agricultural area situated at more than 12 km from the medina). The amount of heat stored in the streets and buildings of the city centre is larger than that stored in the countryside. This amount of energy is returned at night. At the reference point, the medina, the largest temperatures are recorded because of the lack of ventilation, the wall effect caused by narrow streets (0.5 to 2 meters) and the density of buildings (100%) (Dahech, 2012). The coolest points are situated in fields at about 12 km from the medina. Indeed, vegetation turns part of the incident radiation into latent heat through evapotranspiration and therefore stores less solar energy. The mild environment generated by green spaces is undeniable. At night, the public park *Touta* (Sfax), is 2 to 3°C cooler than the surrounding dense areas of the city and provides a cooling breeze for the surrounding environment.

# Is downscaling in modelling necessary?

Climate models are the only tools that enable us to anticipate future climate conditions. Despite the uncertainties usually linked with numerical modelling (scenarios, complexity of physicochemical processes, downscaling), such models can provide a long-term vision at regional scale by taking into account the potential changes in global socio-economic conditions.

*Box 1*
*Mobile temperature measurements using a bike*

Because of the high number of factors influencing temperature, its value changes rapidly over short distances in an urban fragment. The colour and coating materials (land use), the morphology of buildings (e.g. density, height, street widths), the wind and sun orientation of avenues, and the location of vegetated and water areas (from fountains to larger water bodies) are factors that modify the temperature since they have different impacts on the reflection and absorption of sunlight, and on the coupled process evaporation/condensation. Therefore, assessing temperatures in cities, using a bike for mobile measurements (a thermometer is attached to the handlebars at 1 metre above the ground, fig. 2) is one of the most efficient ways of capturing their spatial variation thanks to the speed and the fluidity of movement offered by this type of transport.


*Figure 2*
*Bike with sensors for mobile temperature measurements.*
*Photo: Martin, 2015.*

Several measurement campaigns were carried out between May and September 2015 in Nice over 54 days (approximately a day on two) in the middle of the afternoon. The aim of the study was to record maximum daily temperatures and, even though this was difficult to achieve due to temporal instability and the different timings of peak temperature that depend on the type of space, the resultant mapping remained close to the daily thermal maximum.

In urban and semi-urban areas, temperatures oscillate between 25.5 and 28°C (fig. 3). Sometimes, the variations observed are sensitive over short distances. This can be the consequence of a change in land use (e.g. from concrete coating to a grassy area of land with a loss of 1°C on average over few meters); on a steep slope, the combination of a paved road with a light-coloured bank that directly reflects the sunlight implies an increase in temperature (about 2°C); finally the orientation of the streets and the shadows cast by buildings make for streets that are more or less warm depending on the position of the sun in the sky (in the summer period, at around 3.30-4pm, streets that are orientated north-south are less exposed to the sunlight than those orientated east-west with a difference of 1°C on average).

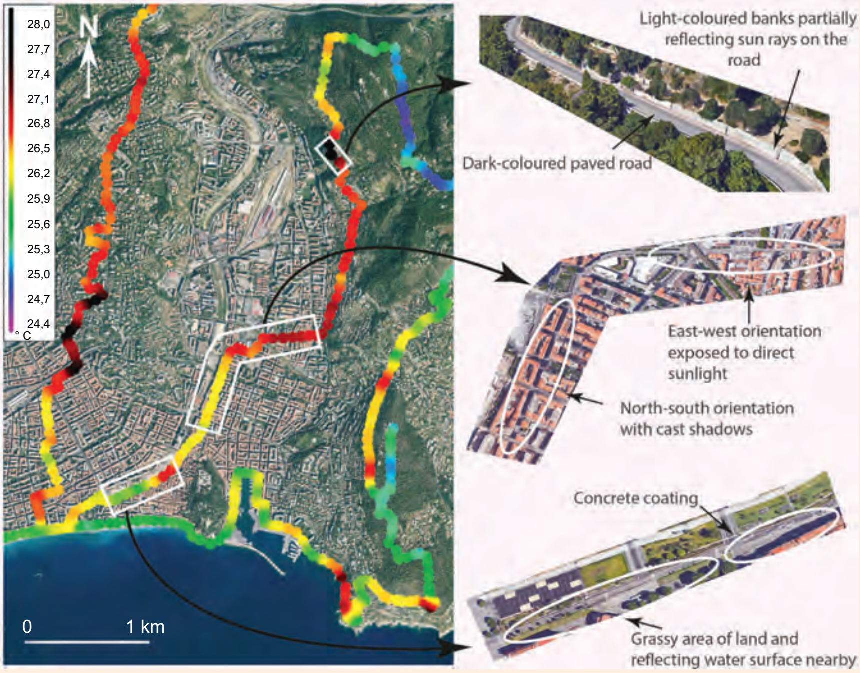


*Figure 3*
*Map and analysis of mobile temperature measurements in Nice in 2015.*
*Aerial photo and 3D perspective: Google Earth.*

## Are models adapted to the urban scale?

Numerous Mediterranean countries rely either on public organisations for modelling with regional climate models, or on collaboration with climate services to develop indexes generated from simulations, depending on specific applied questions (e.g. http://www.climrun.eu/).

However, the RCMs allow for the prospective regional analysis of potential future conditions (e.g. identification of trends, increase in interannual variation), but do not provide answers at the intraurban scale.

Other types of models that are better adapted to urban scales and that enable us to refine the analysis include LASER/F (Najjar *et al.,* 2005) for the urban canyon and TEB/ISBA coupled with the mesoscale atmospheric model Meso-NH for the district and agglomeration. Validation of the model consists of the comparison between outputs and observed field data (Kastendeuch et *al.,* 2010).

Models are also characterized by differing methods of calculation: statistical and/or dynamic (box 2).

The sensitivity of models depends on the temporal and spatial scales used, which explains the difficulty of disaggregating data at the urban “social construction” scale. Moreover, the more parameters there are, the larger the uncertainty margins become, because the interactions of climate phenomena are difficult to simulate in a realistic way.

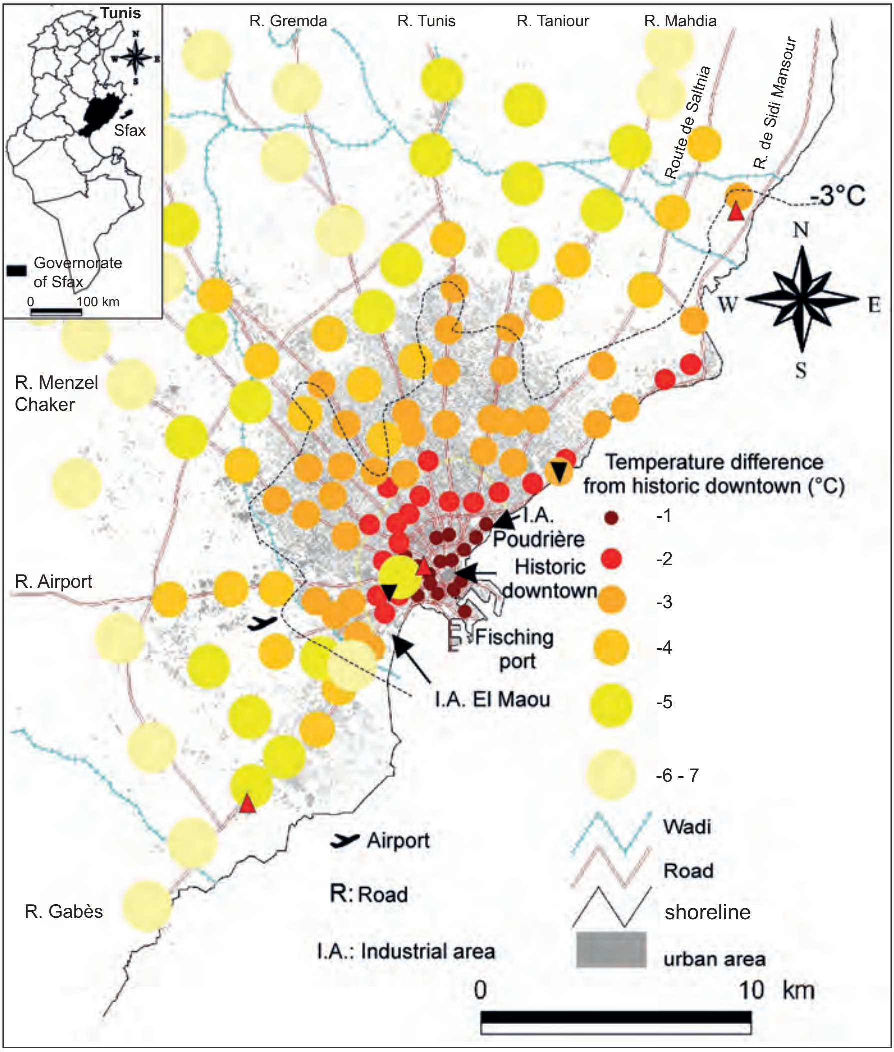


*Figure 4*
*Spatial distribution of night air temperature, at 2 meters above the ground (in °C), in the Sfax agglomeration (Dahech, 2012).*

## Application: simulation of the humidex index for the Nice region

The study of thermal urban comfort, and therefore of the health impact of climate warming on cities, is possible thanks to the availability of local-scale temperature data. However, to best assess the health impact of this variable, it is necessary to weight it with the variable “humidity”. This variable considerably alters our perception and physical strength towards high temperatures. Indeed, the human

**Box 2**
**Downscaling**

Global atmospheric circulation models feature a spatial resolution of several tens of kilometers or more, for instance 12 km in the ALADIN-Climat model (limited area version of the previous model). Such dimensions are however too large to be of use to decision-makers and planners as well as any institutions willing to take action based on fine spatial resolution data (Martin ***et al.***, 2013).

This gap between the need for fine spatial resolution and the outputs provided by models justifies the efforts that have been made for spatial downscaling. Several approaches exist to improve the spatial resolution of climate predictions. Dynamic logic differs from statistical logic. In the case of the former, an RCM will explicitly solve the physics and dynamics of a climate system with a resolution of 12 km at best (e.g. ALADIN-Climat). For the latter option, the improvement of the spatial resolution relies on the search for statistical relationships between local variables and each pixel of GCMs or RCMs' outputs.

There are several methods to statistically refine the spatial resolution of a phenomenon. The environmental regression technique has been selected to substantially improve the spatial resolution of temperatures provided by climate simulations (resolution of 25m using a digital terrain model and up to a few meters with a digital elevation model for urban environments). This approach enables the creation of data from variables that are considered explanatory and that are involved in the studied phenomenon. This is at the interface between a deterministic approach and another based on spatial interpolation since the choice of environmental variables is not random but justified by strong statistical relationships of these data with the phenomenon to be modelled. For instance, the impact of oceanic thermal inertia on temperature can be integrated within a regression model using the "distance to the sea" variable. In urban areas, the evaporation generated by green spaces and/or water features, which provide fresh air, is also considered through the variable "distance".

body reduces its capacity to cool down when the air moisture increases because the perspiration cannot evaporate as readily.

The humidex is an index developed by Canadian meteorologists to take into account this combination of factors. Each humidex interval corresponds with a level of comfort: between 30 and 39 a certain discomfort is perceived, above 40 a strong discomfort, and above 45 there is a threat with possible heat stroke, which is imminent when the humidex is greater than 54. Therefore, by using existing maps of past and future temperatures obtained by downscaling, assumptions on the relative humidity have been made to spatialize the humidex in the city of Nice and its surroundings. The maps show maximum daily values for the month of July (mid-afternoon) within the range of 32 to 41 at the end of the 20$^{th}$ century assuming 80% humidity, and within a range of 43 to 54 at the end of the 21$^{st}$ century under a pessimistic scenario using the same humidity assumption (fig. 5). From a certain discomfort to a strong one, the evolution of the climate will lead to potential or imminent heat stroke conditions.

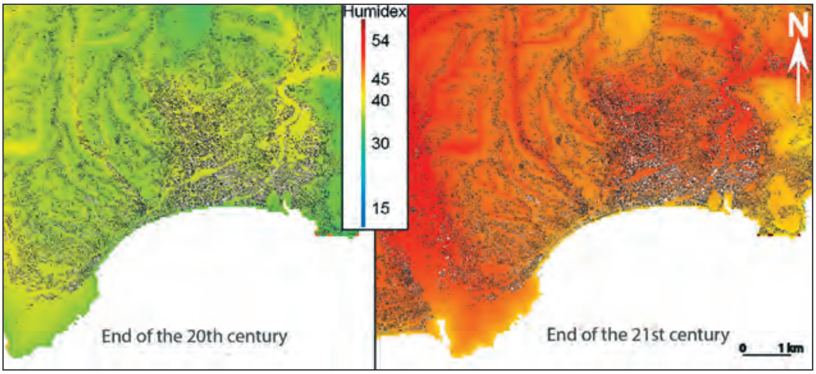


*Figure 5*
*Spatial modelling of the humidex index over a past and a future period for the Nice region.*

In Mediterranean cities, local initiatives are being carried out by various research teams to better understand the urban climate, in particular the spatial and temporal variation of the UHI. Emphasis is also given to studies of summer periods in view of Mediterranean climate characteristics and of the increasing probability of future droughts.

Measuring, understanding and modelling climate at a fine scale enables action to be taken for the transformation of the city by proposing more thought-out urban settlements and structures. New climate change challenges suggest new urban planning methods, and require reliable fine-scale data on climate as well as on impact monitoring through the use of indexes (e.g. humidex) and indicators. These data are crucial to create a tool adapted to urban complexity and specificities. An interdisciplinary approach capable of taking into account the complexity of contemporary cities through co-actions between scientists and political actors is also needed.

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Chapter 2

# Agricultural management, livestock and food security

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## Abstract

Over the centuries, farmers from the countries bordering the Mediterranean have developed a variety of agricultural practices, providing a wide array of commodities that have made the Mediterranean diet world famous. However, climate change projections reveal that some of these practices are at risk because of the expected drier and hotter conditions coupled with soil and water constraints, as well as a higher fire frequency threat. Nevertheless, adapting to climate hazards has long been part of farming practice in this area. The growing of pulses or other drought-tolerant crops (olives, grapes, almonds, etc.), transhumance and the use of rangelands or tree fodder by livestock, as well as water harvesting techniques, are among some of the age-old solutions to erratic rainfall or hot summers. In this chapter, we highlight some of the challenges facing agriculture in the Mediterranean and provide a series of examples of how agricultural and livestock management can be better adapted to climate change.

Reliable metrics are necessary to enable the impact of climate change to be assessed and targeted agricultural policies to be designed. Long-term environmental observatories are essential to improve land management in the context of global change. Modelling the projected effects of current climatic trends shows that regional agricultural import dependence will increase as the impacts of climate change become more severe. Small ruminants (sheep, goats) have a good adaptation potential and can play a food security net role under climate change with a view to responding to the local food demand that emerges with new life styles. Local small ruminant breeds are adapted to harsh environments but this unique genetic heritage is now endangered. Perennial forage grasses are an alternative to cereals due to lower input requirement, year-round soil cover and optimal use of water. Mediterranean fruit trees, although well adapted, face increases in temperature and soil salinity as well as decreases in water availability. They will require improvements such as selection of early flowering varieties (olive), assessment of best pollinating conditions (figs) and salt tolerant rootstock (citrus).



# Résumé

Depuis des siècles, les agriculteurs de la zone méditerranéenne ont mis au point une large gamme de pratiques agricoles à l'origine de productions qui ont rendu le régime alimentaire méditerranéen célèbre dans le monde entier. Les projections climatiques montrent cependant que des risques de sécheresse et de température élevée, associés à des contraintes concernant le sol, l'eau et les dangers d'incendie, menacent certaines de ces pratiques. L'adaptation à l'aléa climatique est néanmoins une habitude ancienne dans cette zone. La culture de légumes secs ou d'autres cultures tolérantes à la sécheresse (olives, raisin, amandes, etc.), la transhumance, l'utilisation des terrains de parcours et du fourrage arboré par le bétail, ou encore les techniques de capture de l'eau, font partie de ces solutions ancestrales au problème de la pluviométrie irrégulière ou des étés caniculaires. Dans ce chapitre, nous présentons certains des défis auxquels l'agriculture méditerranéenne est confrontée et nous proposons quelques exemples illustrant l'adaptation de l'agriculture et de l'élevage au changement climatique. Pour évaluer l'impact du changement climatique et concevoir des politiques agricoles appropriées, des mesures fiables sont nécessaires. Pour améliorer la gestion des terres dans un contexte de changement climatique, des observatoires environnementaux à long terme sont indispensables. La modélisation des effets attendus du changement climatique montre que la région deviendra progressivement plus dépendante des importations agricoles. Les petits ruminants (moutons, chèvres) ont un fort potentiel d'adaptation et peuvent jouer un rôle de filet de sécurité alimentaire en accord avec les nouvelles exigences alimentaires liées à de nouveaux styles de vie. Les races locales de petits ruminants sont adaptées à des

environnements contraignants mais ce patrimoine génétique est désormais menacé. Les graminées fourragères pérennes représentent une alternative aux céréales en raison de leurs exigences modestes en intrants, de leur capacité à couvrir le sol toute l'année et de leur utilisation optimale de l'eau. Bien qu'ils soient bien adaptés, les arbres fruitiers méditerranéens sont confrontés à l'augmentation de la température et de la salinité du sol ainsi qu'à une diminution des réserves en eau. Ils devront faire l'objet d'améliorations comme la sélection de variétés à floraison précoce (oliviers), la prise en compte des conditions de pollinisation (figuiers) ou le greffage sur des porte-greffes tolérants à la salinité (agrumes).



# Introduction

The Mediterranean region is highly exposed to anthropogenic climate change. This will result in a hotter and drier climate, especially during the warm season (Lelieveld et al. 2016). Projected temperature changes in the region are often 50% higher than the global mean temperature increase and are combined with an increased frequency and intensity of droughts (Giorgi and Lionello, 2008).

Crop (wheat, maize and soybean) simulation models forced by climate change scenarios show projected yield impacts varying in the range of -22 to 0% and –27 to +5% for the Northern and Southern parts of the Mediterranean basin respectively (Porter et al. 2014). Adaptation through changes in sowing dates is likely to be difficult, since an early sowing of cereals could be restricted by the lack of adequate rainfall in autumn (Porter et al. 2014). Besides, recent studies have shown that more efficient irrigation systems are required if Mediterranean countries are to protect their water resources at the watershed level (Fader et al. 2016).

Several factors could potentially affect agriculture and livestock production in the Northern part of the Mediterranean basin (Kovats et al. 2014):

– Some of the non-climate trends, such as soil degradation – which is already intense in parts of the Mediterranean basin – may aggravate climate change impacts on agriculture;

– Regional projections show significant reductions in soil moisture, runoff and groundwater resources, which may limit irrigation options;

– Fire frequency and the extent of wildfire significantly increased after the 1970s compared with previous decades as a result of fuel accumulation, climate change, and extreme weather events in the Mediterranean basin, and were associated with strong winds during hot and dry periods. Nevertheless, in the Northern part of the Mediterranean region, the total burned area has decreased since 1985 and the number of wildfires declined from 2000 to 2009, despite the broad interannual variability;

– The Mediterranean basin is expected to suffer multiple ecological stresses due to climate change, such as changes in plant species composition, increase of alien species, habitat losses and degradation, leading to agricultural and forest production losses due to increasing heat waves and droughts exacerbated by competition for water;

– A reduction of spring rainfall associated with higher temperatures is expected in some areas and an increase in groundwater use for irrigation may lead to further environmental concerns (Dono et al. 2016).

Although fewer data are available for the Southern part of the Mediterranean basin, the analysis and modelling of rainfall (Niang et al. 2014) points to a potential significant impact on agriculture. Over the last few decades, the northern regions of North Africa (north of the Atlas Mountains and along the Mediterranean coast of Algeria and Tunisia) have experienced a strong decrease in the amount of precipitation received in winter and early spring. The CMIP5 modelling ensemble projects very likely decreases in mean annual precipitation over the Mediterranean region of northern Africa in the mid- and late 21$^{st}$ century for RCP8.5.

High climatic variability and an inherently challenging climate are nevertheless nothing new for farmers in the Mediterranean. Traditional practices such as the growing of pulses or other drought-tolerant crops (olives, grapes, almonds, etc.), transhumance and the use of rangelands or tree fodder by livestock, and water harvesting techniques (e.g. spade irrigation) are widespread. They are often a response to erratic rainfall or hot summers. Food processing also constitutes a response to climate rigor, e.g. the drying of fruits such as apricots (Syria), figs or dates. The well-known Mediterranean diet (fruits, pulses, legumes, cereals, olive oil, combined with small quantities of meat and dairy products) has proven efficient in staying healthy and reducing risks such as cardio-vascular diseases. Therefore, although being vulnerable to climate change, the Mediterranean region can also be seen as a good example of a healthy food system well suited to the current climate.

In this chapter, we propose a series of examples of how agricultural and livestock management in the Mediterranean region can become better adapted to climate change. We first cover observatories and metrics which contribute to information for decision-making. We then provide a selection of adaptation options covering small ruminants, fodder grass and fruit trees. In a final section, the likely impact of climate change (coupled with demographic expansion and changes in eating habits) on agricultural trade and imports in the Middle East – North Africa region is analyzed. Despite multiple challenges, adaptation and transformation through technological, institutional and market innovations have strong potential in the region. The current knowledge base already provides important indications for the long-term adaptation to climate change of agriculture and food in the Mediterranean basin, but this major challenge is deserving of yet greater research efforts.

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Sub-chapter 3.2.1

# Metrology and quality management

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## Introduction: context and challenges

Demographic growth in countries south of the Mediterranean, combined with the recent migratory upheaval emanating from conflicts in the Middle East, accelerates the urban growth and the spatial concentration of populations on coastlines and estuary zones. According to consistent findings from several foresight studies conducted by the Centre International de Hautes Etudes Agronomiques Méditerranéennes (CIHEAM), the National Research Agency of France (ANR) and the Mediterranean World Economic Foresight Institute (IPEMED), these areas concentrate significant fertile agricultural land but will host 50 million more inhabitants within the coming 25 years.

Both urban demand for food and the pressure on natural resources are rising fast. Local agricultural production of cereals, meat and dairy products is increasingly inadequate to satisfy population requirements. Growing imports of food staples are resulting in food dependency and insecurity for the majority of southern and eastern Mediterranean countries.

The political, economic and social crisis of the 2011 Arab revolutions brought significant difficulties for resource access and management to the fore, leading for example to water shortages, in spite of water availability (less than 500 $m^3$ per inhabitant each year). In conflict situations, competition for resources involves a deregulation of the distribution systems which have long been operating and are the result of complex negotiations between actors to measure consumed quantities and delineate their usage. Under these conditions, the use of fossil vs renewable energy affects not only the quality of agricultural products but also the quality and safety of marketed and processed products.

In order to address these problems, issues which need to be taken quickly into consideration include reducing the negative impact of agriculture, livestock breeding and forestry on the environment, and enhancing positive effects such as carbon storage, soil and plant cover stabilization, or the reduction of runoff and erosion. In other words, agricultural practices which are adapted to changing climate conditions need to be initiated. This requires developing qualitative and quantitative measurement mechanisms negotiated between relevant stakeholders in order to ensure sustainability. Reliable metrics will allow for the efficient measurement of the impact of agriculture and help design agricultural policies targetting environmental protection. At the same time, better management of food waste, consumption and nutritional habits may contribute to adapting agriculture to climatic change over the medium to long term.

All these expected (or existing) disruptions involve strengthening people's capabilities to control agricultural products in order to meet present and future needs. To avoid possible failures against security as well as environmental, social and economic interests, it is necessary to enforce robust conformity assessment systems adapted to the new climate conditions and the growing demand for qualitative products.

The reliability of quality controls of agricultural products is strongly correlated to the availability of skills in the evaluation system. For instance, testing and calibration laboratories should carry out measurements according to well-proven technical prescriptions and produce results leading to the granting of conformity assessments (Lewis and Cooke, 2013).

The strengthening of capacities to control agricultural products needs to be linked to an assessment system harmonized across countries south of the Mediterranean. This system should be based on reliable, long-lasting measurements (Himbert, 2009). Quality and metrology (the science of measurements) will therefore both contribute to the assessment of climate change impact on agriculture. The European project "Quality in agricultural higher education in the Mediterranean area" (QESAMED) highlights the importance of integrating these two domains into higher education and research in order to develop the necessary skills. It is being implemented by the network of the Conservatoire national des arts et métiers (CNAM, Paris, www.cnam.fr) and the Centre de coopération internationale en recherche agronomique pour le développement (CIRAD, Montpellier, France, www.cirad.fr).

# Strengthening conformity assessment systems

There are numerous common social, economic and security interests across countries south of the Mediterranean. Quality control is a great challenge everywhere (Osseni et al. 2015). It will help minimize the risks of product characteristics failing to meet the security, standards or regulatory requirements applying to consumers' health and to the environment. Strengthening capacities for the control of agricultural products is a key component in terms of quality and measurement, which should be coordinated and agreed upon across concerned countries. Skills and means related to the process of quality control have thus to be established and harmonized in the region.

The accreditation of conformity assessment institutions (calibration and testing laboratories, inspection and certification agencies) is essential. It serves to validate practices and skills (organizational and technical) for quality checking. As illustrated in Figure 1, laboratories play a key role in the reliability of controls. They are called upon at all levels and must ensure ethical, impartial and independent outcomes. Therefore, the accreditation of these laboratories must be considered as a precondition.

Control cannot be properly implemented unless the product quality measurement system is itself controlled. Additional resources are necessary for countries to carry out regular and reliable controls.

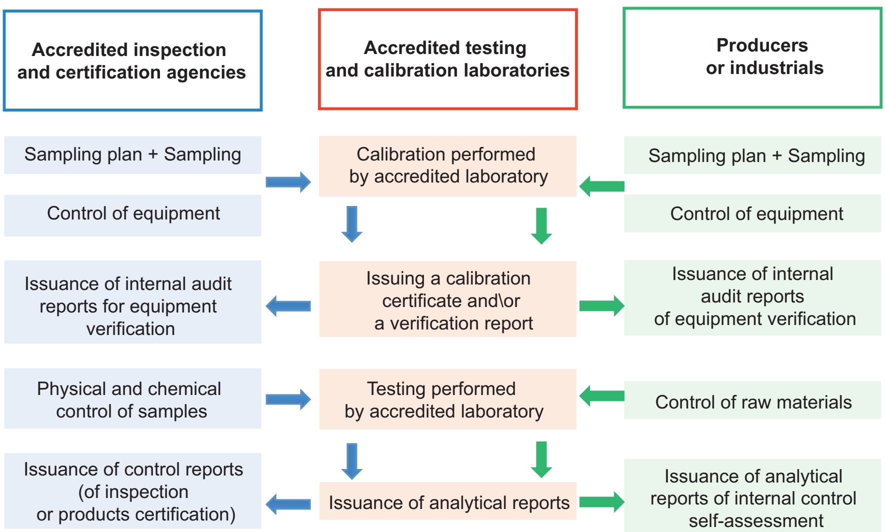


*Figure 1*
*Links between inspection, certification, producers/industrials and testing and calibration laboratories.*

# Ensuring the reliability of controls

The ISO\IEC 17025 standard clearly defines the technical requirements relative to testing, analysis and calibration laboratories. In particular, it requires the evaluation of result uncertainty (e.g. samples of an agricultural product) (Charki and Gerasimo, 2012; Charki and Louvel, 2012). To ensure reliable results, it is also important to control all the factors which may influence results (Fig. 2), i.e. equipment, method, product, environment and manpower.

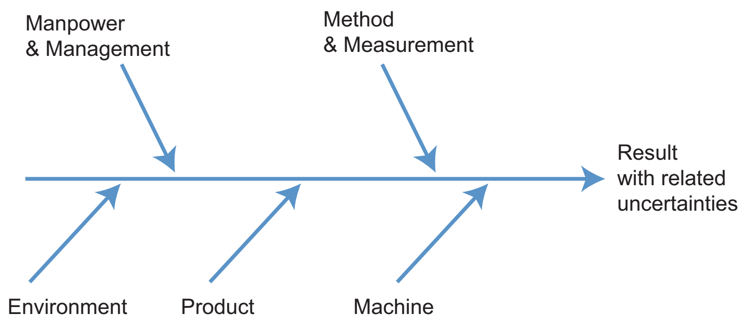


*Figure 2*
*Detailed and up-graded diagram of Ishikawa:*
*5 basic tools of quality management*

The following quality requirements are listed in standards ISO/IEC 17025 (2005) and ISO/IEC 17020 (2012) and need to be checked:

- Traceability requirements
- Maintenance of the equipment used for the analysis
- Control of the calibration or verification for measuring instruments
- Evaluation of uncertainty
- Assessment of the conformity of samples and equipment, etc.

Metrology and quality are thus both joint key factors for the adaptation of agriculture to climate change. They comply with customs' regulations and considerably decrease sanitary risks linked to the consumption of agricultural products.

The equipment used for result reliability ("critical" equipment) needs also to be checked through metrological control. For example, equipment used to analyze pesticide residues or organic contaminants (dioxin, polycyclic aromatic hydrocarbon, melamine, anisole, acrylamide, etc.) or for the dosage of mycotoxins and phytotoxyns in foodstuffs for humans and animals (LAB GTA 21 and LAB GTA 26), such as chromatographic columns (liquid or gas, whether coupled or not with mass spectrometry), ultraviolet-visible spectrophotometer, robots of extraction and purification, volumetric instruments and climate chambers.

# Integrating quality and metrology in higher education and agricultural research

Since 2005, two associations have promoted awareness-raising activities in their field of expertise in the Euro-Mediterranean region: *Quality Association in Research and Higher Education* (QUARES, www.quares.fr) and the *African Committee of Metrology* (CAFMET, www.cafmet.com). The project "Quality in Agricultural Higher Education in the Mediterranean area" (QESAMED, www.qesamed.eu), selected in the 6th call for proposals of the European Tempus IV program, was developed in conjunction with the meetings organized by these groups.

Launched in 2014, the QESAMED project has conducted quality and metrology activities in the Mediterranean area over a three-year period (2014-2016). The main objective was to develop capacities of higher and vocational education systems in French-speaking Maghreb and Middle East countries: Algeria, Lebanon, Morocco, and Tunisia. The project focuses largely on agriculture, including the food industry, and aims to professionalize quality and metrology training in higher education.

The QESAMED project relies on the skills of 23 organizations from 7 different countries, with a threefold purpose:

1. Ensure the initial training in quality and metrology for agronomy students in the Mediterranean area, including distance-learning training adapted to the context of professionals;

2. Raise awareness on quality and metrology challenges underlining competitiveness in the agricultural production sector;

3. Take into account quality and metrology requirements by institutions through research and technology transfer as well as training certification.

The project also supports research transfer initiatives for quality procedures and metrology processes. For instance, the Centre for Analysis and Characterization of Cadi Ayyad University in Marrakech is working towards accreditation and benefits from dedicated support (training courses, evaluations, etc.) by European experts.

The development of a regional network of expertise on quality and metrology in higher education and research is also necessary. It will support mainstreaming quality control in applied research and production units, and as such contribute to the economic development of Mediterranean countries.

# Conclusion and perspectives

Mediterranean countries will be affected by the current ongoing climate changes, and vulnerable populations (e.g. in terms of food security, access to water and energy, etc.), especially in urban areas, will be impacted first.

The need for rapid adaptation of the agricultural sector is a vital challenge for sustainable development in the Mediterranean Basin countries. The awareness of managers and decision-makers of the importance of quality and metrology to sustain progress is essential. Skills improvement is necessary, both for strengthening the autonomous control capabilities and for enforcing the efficiency of innovation and applied research. These skills will contribute to the new paradigm of the ecological transition and ensure the development of a new, more efficient and environmentally friendly agriculture.

By coordinating the efforts of French-speaking countries of the Mediterranean Basin, the European QESAMED project contributes to the development of regional skills on quality and metrology applied to agriculture. Good research practices will enable the development of innovative solutions to best adapt agricultural practices to the challenge of climate change.

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# Long term agro-ecosystem observatories in the Mediterranean

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## Introduction

Alleviating the impacts of climate change is a major challenge facing agriculture in the near future. It is however not the sole challenge, since agriculture is experiencing many other pressures, including a 30 percent increase in global world population, changing dietary patterns and intensifying competition for increasingly scarce land, water and energy resources. In the Mediterranean area, all these challenges are at a very high level since this region already faces a shortage in natural resources and food production and is a hotspot for biodiversity, climate change and population growth.

The adaptation and transformation of Mediterranean agriculture will therefore be necessary for improving productivity and ensuring better management and protection of water and soil resources. To this end, the prerequisites are to identify how both Mediterranean farming systems and climate change will impact soil and water resources over the long term and, in turn, to detect potential levers in agricultural and land management that can alleviate these impacts and favour resilience to climate change.

There are several difficulties involved. First, the nature of the impacts: whether permanent and gradual, or rare and sudden, they are difficult to identify or observe without knowing the base line of the processes. Second, the natural variability of climate and soil often blurs the specific impacts of climate change and agricultural management. Third, the large number of driving factors for water and soil resources makes it difficult to distinguish those that are essential to consider. Finally, there is a need to integrate processes at different scales, e.g. plot, field, catchment and landscape scales. Accordingly, documenting and identifying environmental impacts requires long-term field observations across several scales in order to sort out the processes at different time scales and to different spatial extents. Observations of environmental processes must also be coupled with observations of their human or natural driving factors.

Long term environmental observations can be obtained from natural archives such as ice covers or lake sediments, which enable environmental changes over the millennia to be examined. But archives are not available for all scientific purposes and long-term observatories are therefore needed. According to Loireau et al. (2014), their general objectives are to i) monitor environmental processes, ii) understand the processes at stake and iii) disseminate information. For those observatories that intend to address social issues, the additional objectives are to iv) provide a diagnostic of management options and v) advise managers on new orientations.

In this subchapter we first recall some milestones of long-term environmental observatories. We then present the objectives and main features of the "OMERE" observatories and illustrate with collected datasets the potential contributions of agro-hydrological observatories to better land management in the context of global change; finally, we advocate for intensifying long-term environmental observations in the Mediterranean region.

## The development of long term observatories

One of the earliest examples of a long-term observatory is the long-term agricultural research experiment that started in 1843 at the Rothamsted experimental station in England and enabled the effects of different nitrogen fertilizations on crop growth to be analysed. Other thematically focused observatories set up later include, for example, those monitoring the impact of forest land management on water yield and quality, and floods (e.g. the Hubbard

Brook experimental forest in the US in 1955, Plynlimon in the UK in 1967). A broader thematic initiative took place in 1980 with the US Long-Term Ecological Research program (LTER) which now comprises 26 sites (Robertson et al. 2012), and led in 1993 to the foundation of the international LTER (ILTER), now joined by 43 countries.

In France, it is mainly since 2001 that long-term environmental observatories have become popular (Balland et al. 2001). In fact, at that time, atmospheric and oceanographic sciences and seismology had already set up dedicated long-term observatories, but the call for Environmental Research Observatories (ORE) launched in 2002 by the French Ministry of Research extended the concept to all environmental sciences. Thanks to this call, the long-term agro-hydrological observatories OMERE (Voltz and Albergel, 2002) were set up in 2003. In 2011, OMERE took part in the creation of the French network of drainage basins RBV (portailrbv.sedoo.fr). Other examples of observatories are the TERENO Network launched in Germany in 2008 and the Long Term Agro-ecosystem Research network (LTAR) launched in the US in 2011 (Walbridge and Shafer, 2011).

However, concerning the Mediterranean region, long-term environmental observatories are dramatically lacking. This is especially so for agricultural ecosystems. So far, at the landscape or regional scales, only three Mediterranean agricultural observatories are registered in the ILTER sites map (data.lter-europe.net/deims/global-sites-map), two of them being the OMERE observatories.

## The OMERE Observatories

OMERE (in French “Observatoire Méditerranéen de l’Environnement Rural et de l’Eau”) focuses on the observation of the agri-environmental impacts of soil and water management in typical Mediterranean agro-systems (Voltz and Albergel, 2002). Its specific objectives are to:

i) create records of long term observations of the states and fluxes of soil and water resources as related to records of agricultural management practices in Mediterranean head-water catchments,

ii) study the impact of climate and land use change on water flow, erosion processes and soil-vegetation-atmosphere interactions,

iii) identify the main mechanisms governing long term quantitative and qualitative changes in water and soil resources from field to catchment scale,

iv) support the development of generic agro-hydrological distributed modelling approaches for designing new sustainable management practices,

v) identify levers and methods for a sustainable agricultural management and improved delivery of ecosystem services by Mediterranean agro-systems.


*Figure 1*
*Location of the OMERE catchments.*

OMERE consists of two catchments that are similar with respect to climatic conditions, but differ according to land-use (see Fig. 1). The Kamech catchment (263 ha), located on the Cap Bon peninsula in Tunisia, represents present trends in land use change in the southern Mediterranean, i.e. a progressive intensification of agriculture with full use of the area available for agriculture and an increasing application of fertilizers and pesticides. In the Roujan catchment (92 ha) located in southern France, intensification of agriculture has been present for a few decades, leading to severe water pollution, and land abandonment is now a problem. Monitoring started in 1994 for Kamech and in 1992 for Roujan and includes atmospheric inputs, surface flow, groundwater fluctuations, evaporation fluxes, land management practices, solute and erosion fluxes. More details on OMERE can be found on its web site (http://www.obs-omere.org).

## Examples of outputs from OMERE observation records

### Impact of climate variability on catchment runoff

Mediterranean headwater catchments provide water for lowland irrigated agriculture and for the coastal population. Changes in the amount of water that the catchments deliver may severely affect down-slope areas and populations. Figure 2 shows the relationships between rainfall and runoff that emerges from the time series recorded in the OMERE catchments since 1993. During that period, the two catchments received very similar annual rainfall amounts (medians of 634 and 637 mm/year-1 for Roujan and Kamech, respectively), with very large inter-annual variability. For large and medium annual rainfall amounts, runoff is decreasing in line with decreasing rainfall. The runoff decrease is slightly larger than half of the rainfall decrease. Below a threshold of annual rainfall, no runoff is observed anymore, which occurs 1 out of 4 years in Roujan and 1 out of 10 years in Kamech. It can be anticipated that no runoff will occur during 50% of the years with a 17% and 30% decrease of rainfall in Roujan and Kamech, respectively. These precipitation changes are in accordance with the AR5 IPCC predictions for 2081-2100 under the RCP8.5 scenario: 10-20% decrease in the Roujan area and 20-30% decrease in the Kamech area (IPCC, 2013). An important change in headwater catchment runoff can thus be expected at the end of this century.

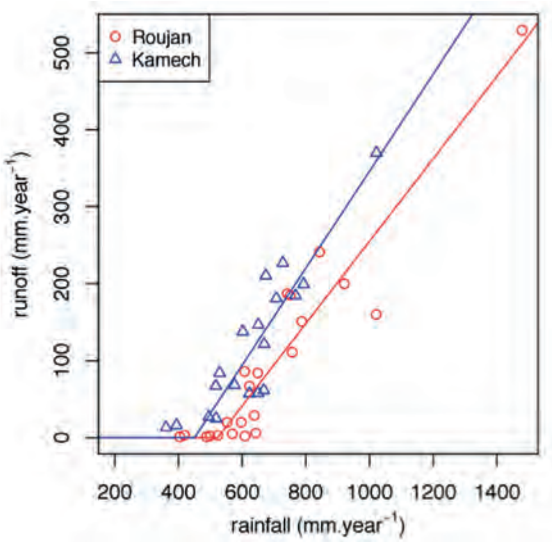


*Figure 2*
*Rainfall-runoff relationships in the OMERE Catchments.*
*The figure covers the periods 1993-2015 in Roujan (France) and 1995-2013 in Kamech (Tunisia).*

## The potential of agricultural management for alleviating the impact of droughts

Agricultural land use has also a large impact on runoff. Rainfall is evidently a major driver of runoff, as can be seen in Figure 2, but a large spread of runoff is observed for a given annual rainfall amount. This can be attributed to differences in the intensity and temporal distribution of rainfall events between years, but also to changes in agriculture practices and catchment management. OMERE provides observations that allow for the quantification of the specific effects of agricultural management on water resources. Figure 3 shows the variability in land uses that exists in the Kamech catchment (Fig. 3a) and the correlated variation in surface runoff between the land uses (Fig. 3b) (Mekki et al. 2006). The annual amounts of surface runoff vary six-fold according to land use. A similar observation was made on the Roujan catchment, where vineyards exhibit twice as much runoff when tillage is replaced by both no-tillage and chemical weeding that favour permanent soil crusting (Andrieux et al. 1998). Accordingly, the influence of land use and management on catchment runoff is even larger than the one expected from climate change, as estimated above. The choice of land use and of management practices therefore appears to be a main lever for controlling catchment runoff and alleviating, at least in part, the expected impact of increasing droughts. Research is now needed to determine how the spatial mosaics of land use can be optimized to meet both the requirements of rainfed agriculture and water harvesting for irrigation needs. Data collected at the landscape scale by observatories like OMERE may then serve as benchmarks for exploratory simulation approaches.

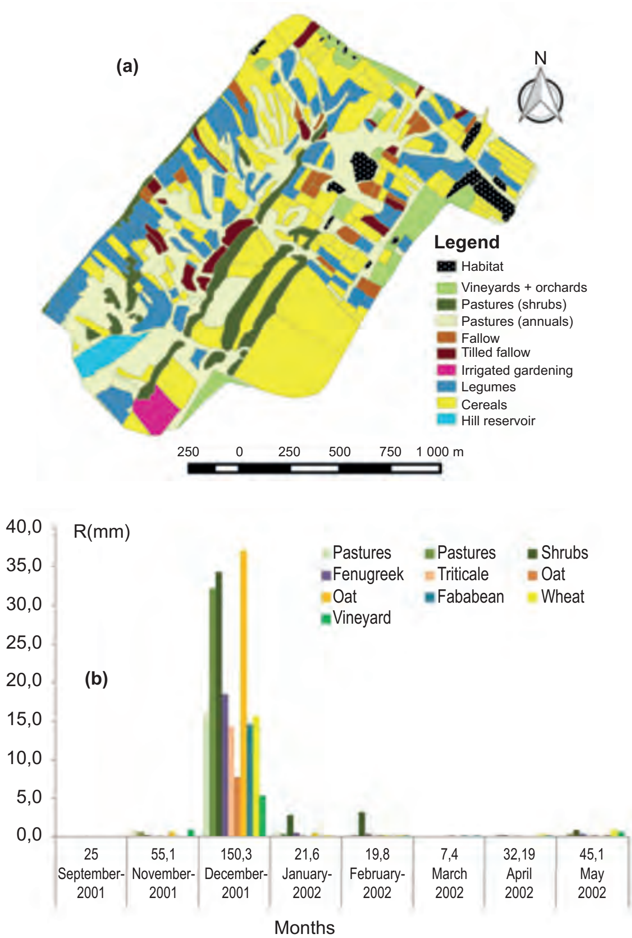


*Figure 3*

*a) Land use map in Kamech, Tunisia and b) variation of monthly runoff amounts R (mm) for different crops from September 2001 to May 2002 (after Mekki et al. 2006). Numbers on the x-axis labels of b) indicate monthly rainfall amounts (mm).*

## Hydrological infrastructures as means for soil and water conservation

In Mediterranean cultivated landscapes, small dams are often used both for protecting downstream areas from flooding and silting and for harvesting water. Stored water enables the temporal shift to be managed between drought periods, usually during spring and summer, and rainy periods, during fall and winter. Dams are therefore levers for agriculture adaptation to climate variability. With a current capacity of 93,000 m$^3$, the water stored at the Kamech small dam is equivalent to 35 mm of rainfall over the whole catchment, corresponding roughly to one tenth of crop water needs. However, all stored water is not necessarily available for agricultural use due to losses, especially infiltration losses that are still poorly quantified. The detailed monitoring of hydrological fluxes in OMERE has led to insights into the rate, variability and control factors of this process. The water balance of the Kamech dam (Fig. 4) reveals that infiltration of stored water is in fact a major loss, two to five times larger than evaporation (Bouteffeha et al. 2015). From a local point of view, infiltration may thus jeopardize the small irrigated area around the water reservoir. However, infiltration may also recharge the regional aquifer and thus increase groundwater resources. Small dam networks constitute a moderate but real water resource for crops. Their actual impacts on water resources must be considered at both local and regional levels. This requires an integrated analysis that can be performed with agro-hydrological models calibrated on reliable hydrological records, as those provided by permanent observatories.

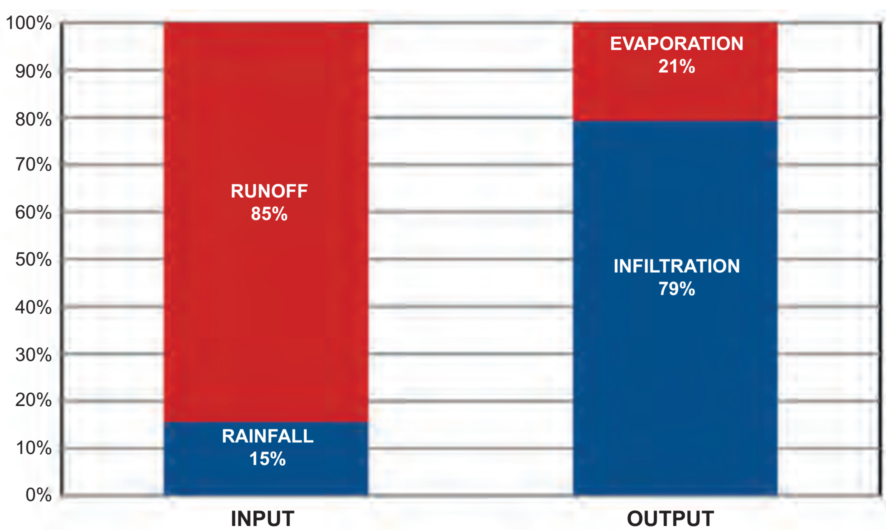


*Figure 4*
*Terms of dam water balance for the hydrologic year 2010/2011 in Kamech, Tunisia. Note that i) runoff corresponds here to the amount of surface water exiting the uphill catchment and entering the dam reservoir and ii) no outflow from the reservoir was observed during the observation period.*

# Conclusion: advocating a long-term agro-ecosystem research network in the Mediterranean

Long-term observations deliver important records that not only help to improve our understanding of agro-ecosystem functioning but also provide quantitative references for sustainable land management. OMERE was one of the first observatories in the Mediterranean area developed to collect long-term observations of agricultural systems at the landscape and catchment scales. More observatories are clearly necessary since the two OMERE catchments represent only partly the diversity of ecological and agricultural systems in the Mediterranean. Moreover, the OMERE observatories are mainly focused on agro-hydrological issues, while other data concerning soil carbon sequestration, green house gas emissions or biodiversity conservation are also needed to address the agriculture and climate change challenges in the Mediterranean.

The development of a network of long-term agro-ecosystem observatories is therefore highly desirable. It would enable the study of a large range of Mediterranean agro-ecosystems, thereby comparing records and processes and analysing their representativeness and variation. It would also enable a large range of issues for the future management of agro-ecosystems to be addressed and favour transdisciplinary research. It requires however that the concepts and needs of long term environmental observatories spread across countries. This depends on the commitment of scientists from different disciplines and institutes.

## Acknowledgements

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# Adaptability of small ruminant farmers facing global change

## A North-South Mediterranean analysis (France/Egypt)

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## Introduction

The Mediterranean basin has seen a doubling of its population during the last 40 years to reach 450 million inhabitants, with one third of its population concentrated in the coastal zone, characterized by a high degree of urbanization. Conversely, during the last century, the hinterland of the Mediterranean coast faced a rural exodus accompanied by a decreasing land pressure that affected landscape dynamics in the North Mediterranean and caused a radical change of collective management in the South Mediterranean, disrupting long-term adaptation practices to climate variability. These changes relate to the urbanization and demographic pressure – with the unavoidable changes of cultural habits and living conditions – and have direct and indirect impacts on natural resources and human well-being in the hinterlands. Since the last decade, the Mediterranean basin has also been considered as one of the 'hotspots' of climatic change, i.e. areas where temperature and rainfall are (and will be) particularly affected (Christensen et al. 2007) therefore reinforcing uncertainty in human activities. These levels of human pressure combined with the burden of climatic changes make these zones particularly vulnerable to future expected changes.

In this context, livestock activities based on small ruminants remain an opportunity to maintain a socioeconomic activity in the arid and semi-arid Mediterranean hinterlands, which represent around 3.2 and 2.25 million $km^2$ respectively (Le Houerou, 1990). At the farm level, livestock relies on the core functions of production, savings and capital, and also employment. Through the use of rangelands, livestock strengthens the links between Mediterranean cities and their hinterland but also between a multitude of institutions from family to the national or supra-national levels. It also occupies a central place in terms of alternative water uses, food, culture and tourism, knowing that the link between city and hinterlands suffers from the externalities of global change in terms of diet and management of natural resources. Nevertheless, while livestock activities have adapted well to recent changes in the short term, by adjusting their mobility and thus their ability to occupy new lands, their mid- and long-term adaptation to ongoing changes in terms of impact on the environment and the society remains uncertain and presents a challenge for both local and regional decision makers.

The choice of a comparative approach between Provence Alpes Côte d'Azur in France (PACA) and the north coastal zone of western desert in Egypt (CZWD) is based on the idea that analyzing the diversity of adaptive processes according to contrasting historical, cultural and socioeconomic contexts can highlight the magnitude of changes and illustrate whether or not adaptive capacities vary according to the context.

## Case studies

Egypt is located in one of the world's most arid regions: Only 3.4 million ha are arable and more than 95% of crop lands are irrigated with the Nile water. The production system is mainly a mixed crop livestock system based on irrigated fodder and food crops and feed supplementation for animals (Tabana et al. 2000). In the rainfed CZWD, populated mainly by Bedouin breeders, we can distinguish four main systems according to the four agro-ecological zones (Matrouh project, 2002): *"(i) a narrow coastal strip, about 5 km inland, which has good alluvial soils and where horticulture is the main farming activity, with livestock and barley; (ii) a mixed production strip, 5-15 km inland, of lower rainfall and soil quality, where a mixed small ruminant-barley farming system prevails with orchards in the wadis (seasonally dry riverbeds) [photo 1]; (iii) a rangeland strip, 15-50 km inland, of semi-nomadic population, largely based on seasonal transhumance; and* *(iv) a zone beyond 50 km inland, where a nomadic population lives on animal production, mainly camels*". Our study was based on a farm survey (175 farms) along a west-east gradient, from rainfed and oasis zones with livestock-crop-tree systems to mixed crop-livestock systems in new reclaimed lands. This gradient allows different agro-ecological and sociological zones to be considered according to the tribe composition of the Bedouin society as well as the influence and proximity of urban life.

*Photo 1*
*Wadi bed, Mixed small ruminant-barley-Orchard (Fig trees) system. Marsa Matrouh.*
*© Cirad, Pascal Bonnet.*

In the French North Mediterranean coastal zone, sheep production is the most prominent type of ruminant breeding. This activity is spread along a gradient of increasing density over the distance from the coastal zone with an increasing specialization in livestock activities to benefit the hinterland. In the PACA region, farms managing flocks of more than 750 head increased by 40% between 1993 and 1999. This specialization was initially made possible by an increase of forage cultivation on released land (benefiting from rural depopulation) and the increased productivity of cultivated forage (sometimes associated with the development of irrigation schemes). The use of uncultivated areas encouraged by recent public policies promoting and facilitating the development of pastures on these lands has further increased this trend (PHAE *Prime Herbagère Agro-Environnementale*, AEM Agro-Environmental Measures, and CAP *Common Agricultural Policy*). In the French context, livestock issues primarily focus on reducing environmental risks exacerbated by global change (biodiversity loss, fire). The assumption is that the structuring of the landscape, to which pastoral livestock practices highly contributed, can promote the adaptation and adaptability of ecosystems. Natural hazards such as climatic uncertainties that disrupt the regularity of available feed resources and environmental changes such as reappearance of predators may question these landscape-level processes. Another issue faced by livestock is its ability to respond to societal expectations in terms of contribution to local development at territorial (local constituency) level. It was thus relevant to analyze and develop the capacity of co-evolution of these livestock systems, paying particular attention to interactions at local constituency level and diversity in management as a resilience factor (Rammel et al. 2003). The research was based on an important data collection system on present and past trends using archived information, and drew up a retrospective and current agrarian description based on interviews.

## Conceptual framework

Figure 1 presents the three 'entities' used in Frazer (2009): (i) the agro-ecological system whose robustness can be appreciated by its natural diversity; (ii) the traditional, formal and informal institutions that increase/decrease the capacities to respond to shocks like climatic ones (drought, flood, etc.); and finally (iii) the family livelihood based on the diversity of assets. This triangular presentation shows the links between each component and explains the whole adaptive process at each level. For instance, traditional or formal institutions can reinforce or reduce the diversity of livelihood or agro-ecological systems by acting on resource distribution (livelihood) and resource use (agro-ecological system). Typically, the south Mediterranean drought policy (feed distribution at low price) has reduced the agro-ecological diversity, leading to over-stocking and desertification on pastureland. The loss of agro-ecological diversity has reduced one of the major adaptive processes of livestock systems based on mobility and has consequently led to an increase in rural exodus. So the question we now face is: *how does the institutional network influence livestock management and, as a consequence, the agro-ecological system?*

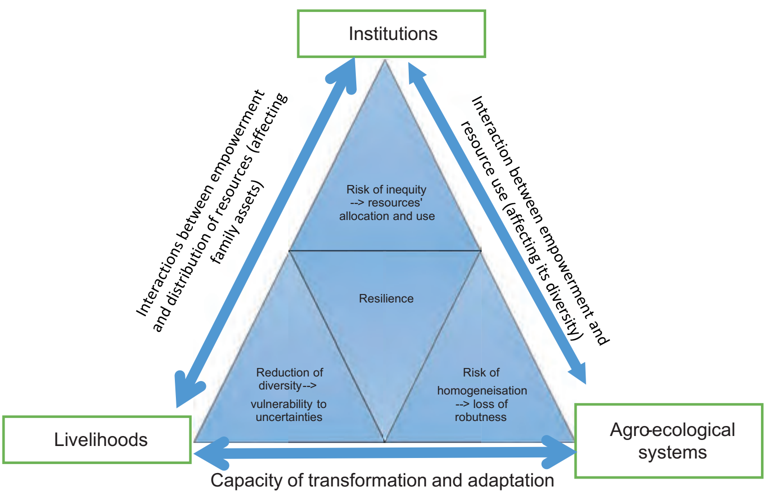


*Figure 1*
*The three entities for analyzing the adaptive process (adapted from Frazer, 2009).*

# Results

Two main groups of institutional stakeholders with direct or indirect impacts on livestock development have been identified in the two countries: (i) the breeders' network in direct link to the livestock activity; and (ii) the local development agencies comprising the local constituency (territory) or government agents.

Breeders' networks consist of similar agents with common objectives (meat production and resource access) but are under different authorities and rules: families and tribes in Egypt *vs.* development-oriented groups in France. At the two sites, this group reflects the objective and power of large breeders. The local development groups (territorial agencies in PACA or development projects and governorate officials in CZWD) are similar from the point of view of 'public policies' but differ in their local involvement. In PACA, the majority of stakeholders involved in these territorial entities are from the region itself, while in CZWD, most of them come from Cairo (at decision level). In PACA the trend is to give more financial autonomy to the region or municipalities, whereas in CZWD, these stakeholders are merely the relay of the central authority. This has had a major impact in terms of local development pathways.

Both countries exhibit dynamic changes in livestock activities in connection with breeders' networks which are the prevalent socio-economic actors. A typology of breeders based on mobility and animal performance in the agro-pastoral region of the CZWD shows that only the largest breeders were able to maintain long transhumance during the last 15 drought-years (1995-2011). The rate of profitability remained low due to high lamb mortality and the degradation of available resources. On the other hand, some small and medium size breeders have reduced feed supplements (mainly grains), adopting a strategy of maintaining a minimum productive livestock (lifesaving strategy; Photos 2 and 3), while others have increased feed supplements for maximizing the profitability per animal during drought periods, depending on other sources of income. In addition, the degree of diversification in off-farm activities is strongly correlated to traditional tribal organization (Alary et al. 2016). In PACA, the main dynamics are related to: i) the market, through the organization of short circuits of animal products (directly from producers to consumers), adapted to the new urban and touristic demand; and ii) a huge increase in labor productivity, taking advantage of grazing large flocks in large areas (Aubron et al. 2016). Large breeders' networks are therefore key-actors in maintaining the socio-economic functions of livestock activities at the two sites. They develop the economy in harsh environments, through the market in the North and through mobility in the South, with the risk of the social exclusion of small breeders that are not able to maintain the transhumance and are not well structured.

The role of local development agencies is more ambiguous. In CZWD, the extension of orchards through *wadi* development by development projects (coupled with the settlement policies of the 60s), has deeply transformed the traditional pastoral system based on mobility towards a settled agro-pastoral system, with a varied impact on the agro-ecological system and family livelihoods. This development has favored private land tenure and increased farm diversity income, to the detriment of the collective management of natural resources which used to be a safety net for small farmers. It has also deeply affected the traditional tribal power that was based on social land management at a local level. The weakening of tribal power due to land ownership is inescapably reducing its social security role in the Bedouin community in the face of hazards including drought. This process has also been favored by recent social changes in connection with demographic growth and widespread urban life-style. In PACA, while local authorities may have a significant social role in helping small breeders make a living, their role is modest for the majority of medium and large breeders who benefit from national and European subsidies. This has favored the re-emergence of transhumant models (summer and winter mobility) within different environmental programs (brushing and biodiversity; fight against fire; tourism development), including mobility beyond administrative PACA areas.

*Photo 2*
*Grazing in poorly developed barley field. Marsa Matrouh.*
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*Photo 3*
*Storage of barley straw in dryland area. Marsa Matrouh.*
*© Cirad, Pascal Bonnet.*

# Discussion and conclusion

Results at the two sites show that the local (territorial) perception of development is often far removed from the spatial dynamics of livestock that generally favor a diversity of livelihoods at landscape level. An approach based on the administrative borders of the local constituency prevents mobility-based coherent livestock management, although mobility, driven by agro-ecological conditions and stakeholders' networks, is the main livestock adaptive strategy in the face of climate change. Nevertheless, these networks have favored agricultural development (mainly through irrigation in PACA or wadi development with orchards in CZWD), and consequently the emergence of a new integrated livestock - crop model based on local fodder and concentrate in CZWD and a pastoral model in PACA to face loss of lands newly devoted to high yield irrigated cropping systems. This shows the capacity of livestock activities to reach new agricultural areas (therefore adapting to land pressure) but also to respond to local food demand emerging with new life styles. This permanence, yet adaptability, of livestock confirms its role as a security net in this type of harsh environment.

The use of the Fraser framework has raised questions about the place of an institutional approach in understanding the complex transformation of the livestock system. This framework highlighted the differentiated roles of local development groups to support small farms and of socio-economic groups (such as tribes or breeders' associations) to maintain the spatial adaptive capacity of livestock activities facing Mediterranean challenges, including climate change. The adaptability of small ruminant systems appears to be a social and economic safety net and could be part of an environmental protection strategy, while recognizing the roles of stakeholders' organizations such as tribes or breeder associations. They should be given careful consideration in future local policies.

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# Managing genetic resources of small ruminants in a context of climate change

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## Introduction

Locally adapted breeds of livestock are of major interest as reservoirs of biodiversity. They may play a key role in ensuring the sustainability of the breeding sector in a changing climate. The Mediterranean Basin is characterized by a wide diversity of small ruminant breeds, and more specifically, North Africa and Turkey constitute remarkable dry ecosystems which have enabled the emergence of breeds showing strong adaptation to harsh environments. This unique genetic heritage appears clearly endangered. One of the main threats is the deep lack of knowledge concerning the small ruminant livestock in these areas – some breeds have probably disappeared even before being recorded. Another issue concerns the erosion of the livestock gene pool with anarchic cross-breeding practices leading to genetic dilution and replacement of local breeds by exotic ones or by a reduced number of native breeds among the most productive. The recent availability of high-throughput sequencing is very promising, enabling the identification of unique allelic combinations underlying adaptation traits of the utmost importance in this context of global warming.

# Context

The majority of sheep and goat populations are found in developing countries and play a significant role in their national economies. Indeed, the ability to tolerate harsh climates and thrive on poor quality diets makes them one of the few species able to take advantage of low input farming systems. Breeds of small ruminants have evolved over the centuries managed by traditional pastoralists, enabling the emergence of wide diversity and of strong adaptations to a range of diverse environments. In developed countries the situation changed with the emergence of the breed concept (200 years ago), with a shift from "soft" selection to "harsh" selection for maximizing productivity (Taberlet 2008). As a result of practices focusing on performance improvement, genetic resources have been lost, because of the homogenization of industrial breeds subjected to strong selection and moreover, because of the replacement of traditional breeds by a limited number of high-performance breeds. Finally, intensive commercial production systems have led to the rupture of the link between the breed and its environment (Hoffmann 2010).

Today, worldwide livestock diversity is threatened and the Mediterranean area is no exception: one domestic breed disappears every month in the world and 30 percent of livestock breeds are considered at risk of extinction (Food and Agriculture Organization (FAO), 2015). Animal genetic diversity determines the potential for adaptation in changing environments; hence preserving the biodiversity is crucial for the breeding sector, especially in a context of climate change.

The Mediterranean Basin is characterized by semi-arid and arid areas which are noted for their desert climate in their southern part (mainly located in North Africa). Moreover, dryland mountain ecosystems, mostly encountered in Turkey and North Africa, represent extremely heterogeneous environments considered as biodiversity hotspots (FAO 2011). Breeds locally adapted to these particular ecosystems are the outstanding result of unique evolutionary phenomena, as they have developed the necessary specific features to deal with harsh environments (water scarcity, extreme hot and cold temperatures, unpredictable long drought periods, etc.). In the context of climate change, these highly resilient breeds are of primary interest. These countries, on the frontline of the climatic evolutions, are particularly vulnerable to the negative impacts of climate change. On the other hand, their livestock genetic heritage – a true reservoir of diversity – appears to be essential, offering a possible solution to deal with the global warming issue and related new diseases.

Here we focus on the locally adapted breeds of particularly dry areas, and dry mountains of the Mediterranean Basin (i.e. North African countries and Turkey), with a view to identifying the major threats affecting them and the genetic field of investigation which could be developed with the aim of making agro-ecosystems of the Mediterranean area more resilient. This is a fundamental condition to ensure sustained - and if possible improved - productivity levels despite unfavorable environmental conditions.

# Knowledge of Mediterranean small ruminant stock

In DAD-IS, the Domestic Animal Diversity Information System hosted by FAO (http://dad.fao.org/), breeds are classified in two groups (i) "local breeds" (i.e. breeds defined in the database as "occurring only in one country" and hence likely to develop adaptations to particular environments) and (ii) "transboundary breeds" (i.e. "breeds that occur in more than one country"). We have compiled this information in order to draw up an inventory of the current state of small ruminant "local breeds" in the Mediterranean area, considering the countries that surround the Mediterranean Basin and for which information is available (i.e. Albania, Algeria, Bosnia-Herzegovina, Croatia, Cyprus, Egypt, France, Greece, Italy, Israel, Libya, Malta, Montenegro, Morocco, Portugal, Slovenia, Spain, Syria, Tunisia, and Turkey). The term "local breeds" does not strictly include "locally adapted breeds" (i.e. "breeds which have been in the country for a sufficient time to be genetically adapted to one or more of traditional production systems or environments in the country" (FAO 2012)) which are the focus of this article; indeed a substantial number of "transboundary breeds" are also adapted to local environments. Hence the information available in DAD-IS leads to an underestimation of the diversity of breeds showing particular suitability for extreme environments (FAO 2012).

The analysis of the DAD-IS data-base shows that 25.2% of local goat breeds and 27.7% of local sheep breeds recorded in the world are concentrated in the Mediterranean area. Hence it appears that more than a quarter of the worldwide small ruminant diversity can be found in an area corresponding to only a few percent of the worldwide arable land surface (according to the World Bank database of surface of arable land by country (http://data.worldbank.org)). This richness has been shaped by the substantial diversity of the environments found in this area. Indeed, The Mediterranean Basin can be seen as a patchwork of nested habitats, in which various combinations of a range of variables (temperature, rainfall, altitude, topography, geology, ground vegetation, soil nutrients, etc.) are the source of the remarkable diversity encountered. Moreover, the emergence of the wide diversity of small ruminant breeds was largely stimulated by the strategic location of the Mediterranean Basin, at the crossroads of three continents (Europe, Africa and Asia), giving the area a major role in trade and economic exchanges, that largely favored the diffusion of breeds around the Basin.

The number and risk status of small ruminant local breeds in the Mediterranean area (see Table 1) shows that 42.7% of the local breeds are endangered or extinct while there is no information concerning the risk status for 19.1% of them. This percentage of breeds classified as "unknown" is particularly high in developing countries, with a mean of 45.5% considering North African countries (i.e. Algeria, Libya, Egypt, Morocco and Tunisia). Moreover, it appears that France, Italy and Spain account for 56.2% of Mediterranean local breeds, whereas North African countries represent no more than 11.4% of the Mediterranean livestock. This result is probably due to a lack of information, inducing a biased picture of the Mediterranean livestock. Indeed, Scherf et al. (2008) have raised the issue of the underestimation of breeds in dryland areas, with a significant number not officially reported. This implies that some uncharacterized breeds may have disappeared without being recorded. The situation varies depending on the country considered; Morocco, Egypt and Turkey report quite substantial numbers, whereas Algeria Tunisia and Libya show clear underreporting (accounting for less than 8% of the North African livestock). However even for Morocco, Egypt and Turkey, the good levels of reporting are offset by the limited knowledge of the breeds (with 79.2% of the Moroccan breeds classified as "unknown", given that most information available in the database dates back to 2007 and has not been updated since).

*Table 1*
*Number and risk status of small ruminant local breeds in the Mediterranean area according to FAO DAD-IS database.*

| Country | Number of loc. breeds (sheep and goats) | % of loc. breeds in the Med. Bas. | % of endangered breeds* | % of breeds extinct | % of breeds with "Unknown" status | % of breeds with "Not at risk" status |
|---|---|---|---|---|---|---|
| Albania | 29 | 6.3 | 17.2 | 48.3 | 6.9 | 27.6 |
| Algeria | 4 | 0.9 | 0 | 0 | 25 | 75 |
| Bosnia-Herzegovina | 6 | 1.3 | 0 | 0 | 83.3 | 16.7 |
| Croatia | 12 | 2.6 | 16.7 | 0 | 16.6 | 66.7 |
| Cyprus | 6 | 1.3 | 33.3 | 33.4 | 0 | 33.3 |
| Egypt | 20 | 4.3 | 5 | 5 | 40 | 50 |
| France | 70 | 15.2 | 11.5 | 52.8 | 0 | 35.7 |
| Greece | 29 | 6.3 | 17.2 | 20.7 | 24.1 | 38 |
| Italy | 121 | 26.5 | 42.1 | 15.7 | 6.7 | 35.5 |
| Israel | 2 | 0.4 | 0 | 0 | 100 | 0 |
| Libya | 2 | 0.4 | 0 | 0 | 50 | 50 |
| Malta | 1 | 0.2 | 0 | 0 | 0 | 100 |
| Montenegro | 7 | 1.5 | 42.8 | 0 | 0 | 57.2 |
| Morocco | 24 | 5.2 | 0 | 0 | 79.2 | 20.8 |
| Portugal | 19 | 4.1 | 0 | 5.3 | 68.4 | 26.3 |
| Spain | 67 | 14.5 | 35.8 | 9 | 6 | 49.2 |
| Slovenia | 7 | 1.5 | 57.1 | 14.3 | 0 | 28.6 |
| Syria | 2 | 0.4 | 0 | 0 | 100 | 0 |
| Tunisia | 3 | 0.6 | 0 | 0 | 33.3 | 66.7 |
| Turkey | 30 | 6.5 | 6.7 | 10 | 43.3 | 40 |
| Total | 461 | 100 | 23.2 | 19.5 | 19.1 | 38.2 |

*breeds with "Critical", "Critical Maintained", "Endangered" or "Endangered Maintained" risk status in DAD-IS (2016) allowing for the fact that most information has not been updated since 2007; Med.Bas.= Mediterranean Basin; loc. breeds=local breeds.

Hence it can be concluded that one of the main threats to the local breeds of Turkey and North Africa, and more generally to local breeds located in developing countries, is a clear lack of knowledge (with breeds unreported and missing or unreliable data for the reported breeds). Lack of infrastructure, lack of organization for the breed sector, areas of political instability, and a policy of disinvestment, amongst other reasons, are responsible for the lack of knowledge for the local breeds of these areas.

## Genetic erosion of locally adapted breeds

A productivity-only objective often appears to be detrimental for locally adapted breeds. Indeed, most of these breeds are poorly productive, and the economic pressure leads farmers to carry out unsupervised cross-breeding (i.e. not in the framework of selection plans) hoping to increase animal conformity, and/or to replace native breeds by exotic ones or by a reduced numbers of local breeds among the most productive. In Algeria for example, one native sheep breed, Ouled-Djellal, which is considered more productive, accounts for more than 63% of the Algerian sheep population. Crosses between Ouled-Djellal and local Algerian breeds are a current practice by farmers , so that four breeds have been found to be highly genetically admixed with the Ouled-Djellal (Rembi, Taâdmit (Gaouar et al. 2015), Barbarine and Berber (Gaouar et al. 2016)). The Berber is considered to be the most ancient and primitive sheep breed of the Maghreb and the genetic dilution of this breed represents a great loss for the worldwide livestock genetic heritage. The other local breeds of Algeria are under high risk of disappearance (Iniguez 2005) because they are largely abandoned and suffer from high census contraction.

Admixture can also be reported among Egyptian goats (Elbeltagy et al. 2016), Turkish sheep (Yilmaz et al. 2015) and among Tunisian sheep (Kdidi et al. 2015). The situation appears different in Morocco, where a national strategy entitled "Plan Moutonnier" (sheep plan) implemented in 1980 (MAMVA 1980) provided substantial support to preserve most local sheep breeds, allowing the identification of breeding areas and monitoring performance. The plan also defined a very limited number of areas where it was allowed to introduce exotic breeds. The current high genetic diversity of Moroccan sheep compared to industrial and indigenous sheep from other countries shows the effectiveness of this strategy in preserving small ruminant genetic resources of Morocco (Benjelloun 2015).

Hence genetic erosion, via indiscriminate cross-breeding and breed replacement, is a major threat for local breeds of North Africa and Turkey, leading to the homogenization of this unique reservoir and to the loss of allelic combinations of potential interest in a climate change context.

# Genetic uniqueness of locally adapted breeds

Local breeds are largely shaped by natural selection and are hence highly connected or "locally adapted" to their natural environment. Local adaptation could come either from the standing genetic variation (existing variation in a population) or from novel mutations bringing new alleles that are advantageous and thus become selected in a given environment. Current findings suggest that most local adaptations stem from standing variation, rather than from new mutations (Savolainen et al. 2013). Selection (natural and artificial) has left its footprint in the genome, a process known as "selection signature". Indeed, positive selection favoring local adaptation is expected to increase the frequency of an allele, and in the same time, the length of the haplotype (extent of DNA segment) associated with the selected allele, relative to those that are not under selection. Today, given the availability of dense marker panels, scientists have the possibility to track these selection signatures and hence to identify allele of primary importance in adaptation to harsh environments.

Recent studies within the EU-funded "NextGen" project (2010-2014) have used whole genome sequences (WGS) to assess genetic resources in various domestic (Moroccan and Iranian indigenous breeds and a worldwide panel of cosmopolitan breeds) and wild populations (bezoars and Asiatic mouflons). Iranian domestic breeds and wild populations were sampled from the presumed domestication centre (Fertile Crescent) with the assumption that genetic diversity in these individuals is at its highest level and would decrease regularly along the migratory routes as described by Bruford et al. (2003). As expected, the NextGen studies identified a very high variation in Iranian domestic populations and in wild populations (Fig. 1); more surprisingly Moroccan breeds were also found to be highly diversified (in numbers comparable to Iranian breeds, Fig. 1) in spite of the fact that Morocco represents the end of a migratory route and hence was expected to show lower variability.

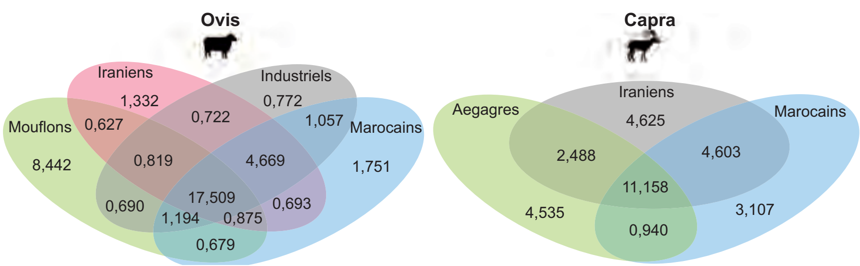


*Figure 1*

*Venn diagrams showing the number of exclusive and shared alleles (in million) in various sheep and goat populations. Source: Benjelloun 2015. Mouflons=Asiatic mouflons (wild populations), Aegagres=Bezoars (wild populations), Iraniens=Iranian domestic breeds, Marocains=Moroccan domestic breeds, Industriels=Cosmopolitan sheep breeds.*

These results indicated that each indigenous and wild population constitutes a unique reservoir of millions of alleles (standing variation) making them a potential source of adaptation of sheep and goats in the context of global changes. Moreover, this project studied the whole genomes of hundreds of local sheep and goats representing Morocco-wide diversity in terms of ecology, climate and geographic origin. An approach called “landscape genomic” was used; it involved correlating allele frequencies with several environmental factors in order to identify selected alleles (selection signatures) probably involved in adaptation to harsh environments. This approach was applied jointly with a population genetics analysis. The outcomes highlighted several sets of alleles and genes that probably play a role in local adaptation to extreme altitude, slope, rainfall and temperature; e.g. some alleles within genes involved in respiration and heart function were identified as playing key roles in adaptation to high altitudes (Benjelloun 2015). Candidate genes for adaptation to similar environments were generally different between sheep and goats, suggesting different adaptive mechanisms in both species and even between two breeds in one species (e.g. panting/sweating to adapt to desert environment in two Moroccan goat breeds; Benjelloun et al. 2015).

Hence, the neutral and adaptive remaining genetic diversity of each local breed could represent a unique treasure that might be needed for the preservation of the species in the current context of environmental changes. Specific strategies should therefore be designed to halt the current loss of autochthonous breeds around the Mediterranean and elsewhere. Moreover, local breed improvement programs have to be planned in order to increase the economic productivity of the local breeds and thus make them more attractive for breeders.

*Photo 1*
*Herds of local sheep and goats, Morocco, High Atlas, Imilchil (altitude: ~2300 m).*
*Badr Benjelloun, 2008.*

*Photo 2*
*Moroccon local sheep (Timahdite breed), Morocco, Middle Atlas, M'rirt (altitude: ~1100 m).*
*Badr Benjelloun, 2007.*

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Sub-chapter 3.2.5

# Fodder grass selection in the Mediterranean

## The role of summer dormancy

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## The importance and sustainability of grasslands and forage crops in the Mediterranean

Around the Mediterranean Basin, crop-livestock farming systems contribute significantly to the rural economy. In southern Europe, livestock farming provides high added-value animal products (typically cheese and meat) but the decline in grazing pressure over the last few decades negatively impacts the landscape, since it results in shrub encroachment and greater fire hazards. In Northern Africa, animal production is widespread and mostly extensive, with a strong negative impact because of overgrazing on rangelands. However, an increased production of animal products is required to satisfy the needs of growing populations (Delgado et al. 1999, FAO, 2009). In Morocco for example, public actions ('Plan Vert') are implemented to foster livestock farming. In all cases, a key driver for the sustainability of animal production is self-sufficiency in on-farm forage supply to counterbalance the increasing cost of imported feed stuff (Abdelguerfi and El Hassani, 2011, Taher Sraïri, 2011).

Throughout the Mediterranean Basin, rangelands and grasslands account for 50% of the land surface and about 270 million ha in the arid and semi-arid zones receiving 100-400 mm annual rainfall (CIHEAM, 2009). They provide forage resources as well as many ecosystem services, including carbon storage, limitation of soil erosion, water catchment and biodiversity preservation. However, in the southern Mediterranean countries, the area available for grazing is diminishing due to the expansion of rain-fed annual cereals, to meet increasing demand for human food (Lelièvre and Volaire, 2009). Millions of hectares of fallow land and rangeland have disappeared while stocking rates have increased because of subsidized imported grain and by-products. Grazing at higher stocking rates is thus allocated to dryer and poorer rangelands: the remaining rangeland is drastically degraded due to overgrazing, leading to a dramatic loss of biodiversity, vegetation cover, greater soil erosion and a diminishing ability to provide ecosystem services. Perennial grasses dominate in most natural grasslands and provide the principal nutrition for ruminant livestock.

However, the genetic diversity of these palatable species is declining due to habitat destruction and overgrazing (CIHEAM, 2009). In the Northern Mediterranean countries, stocking rates tend to decrease along with an increase in extensive permanent pastures that cannot provide sufficient forage resources at all seasons. As a consequence, and around the whole Mediterranean basin, complementary forage crops are crucial to securing farming systems and increasing the productivity and stability of animal production.

However, the resilience of both native and sown grasslands is threatened by increasing aridity due to climate change (I.P.C.C., 2014). Extreme events and severe heat waves are expected to become more frequent and a decrease in summer precipitation will lead to more frequent and more intense droughts, particularly in Southern Europe (Lehner et al. 2006). In the Mediterranean Basin, the rate of warming may lead to an additional month of summer (Giannakopoulos et al. 2009). This increase in water-shortage also intensifies in winter since ten of the twelve driest winters since 1902 have occurred in just the last 20 years (Hoerling et al. 2012). Therefore, pasture establishment failures and long-term degradation from drought are expected to become more common.

Under both this greater incidence of drought and increasing population pressure, the amount of water available to agriculture is declining drastically in Mediterranean areas (CIHEAM, 2009). Rainfall use efficiency for forage production must be therefore improved in both native rangelands and rain-fed forage crops. Under these chronic water shortages, perennial forage species have a number of advantages in comparison to the predominantly used annual species including (1) fewer inputs with less field preparation and fertiliser requirement, (2) year-round soil cover reducing the risk of intense soil erosion, (3) optimal use of water throughout all seasons thus enhancing forage production in particular in autumn when cereals are not yet established and (4) greater flexibility because of the multiple uses of these species (grazing, hay, silage). Perennial grasses are therefore an excellent alternative to cereals, contributing to reduce production costs, halt rangeland degradation and confer greater security overall to rain-fed agricultural systems (Lelièvre and Volaire, 2009).



# Improving perennial forage grasses in the Mediterranean

Attempts to improve productivity of rain-fed and natural pastures in semi-arid Mediterranean regions by the introduction of cultivars bred in more favourable temperate areas have repeatedly proven unsuccessful (Lelièvre and Volaire, 2009). At present, most cultivars of grass species including cocksfoot (*Dactylis glomerata* L.) and tall fescue (F*estuca arundinacea* Schreb.), are bred in and for higher rainfall temperate climates with several hundred cultivars already registered (OECD, 2010). Unfortunately, these temperate cultivars are poorly suited and do not survive the severe summer water deficits of Mediterranean summers (Lelièvre et al. 2011). Due to very limited breeding work carried out in Mediterranean areas, the number of cultivars adapted to summer drought and available to farmers is extremely small: five cultivars of tall fescue and cocksfoot (Lelièvre and Volaire, 2009), all originating from North African germplasm. The development of new innovative perennial grass cultivars produced from Mediterranean selected germplasm is fundamental (Abdelguerfi and El Hassani, 2011) both for the restoration of rangelands and the development of forage crops with enhanced summer drought adaptation and high productivity during the cooler rainy seasons.

In Mediterranean areas, the adaptation of perennial herbaceous plants depends on their long-term persistence mediated by the ability of plants to survive successive summer droughts (Norton et al. 2016). Grasses have developed different adaptive strategies, such as dehydration avoidance/delay and dehydration tolerance to persist through successive summer droughts. However, genotypes with the highest survival rate of the most arid conditions exhibit responses associated with summer dormancy (Volaire and Norton, 2006). This adaptive trait has been developed specifically by perennial herbaceous species subjected to the predictably long and intensely dry summers characteristic of southern Mediterranean environments. It ensures plant survival by maintaining the viability of meristems during the hostile summer. There is a growing interest in this trait since, in cocksfoot and tall fescue, summer dormancy improved survival by up to 30% during long intense summer droughts (Norton et al. 2006). In Mediterranean environments, perennial grasses with summer dormancy have a longer grazing season than annual species. They provide earlier and more sustainable herbage due to fast re-growth at the onset of autumn rains, and make better use of residual moisture at the end of the cooler growing season. However, the environmental factors associated with the induction and the relaxation of this trait remain unclear (Ofir and Kigel, 2006, Volaire et al. 2009) and need to be clarified to design ideotypes and crop management suited to local environments. Unravelling the relationships between plant stage and dormancy induction will also provide key knowledge to understand drought resistance in autumn-winter (establishment stage) when summer dormancy is not expressed. While the winter dormancy of plants growing in temperate climates is well understood, the summer dormancy trait occurring in plant species from Mediterranean-type areas has been little studied even though it has the potential to greatly improve forage crops.

Moreover, it is recognized that highly efficient forage crops are mixtures combining grasses and legumes in order to maximise nitrogen acquisition from legume fixation, reduce fertilization inputs and produce high protein forage. The very low water use of dormant grasses in summer has been shown to reduce competition and enhance the functional complementarity of resource use between associated components (Volaire et al. 2014). Lucerne (*Medicago sativa* L.) is the main perennial legume crop of the Mediterranean basin. Although mainly cultivated under irrigation in the region, recent efforts have been made to develop better drought-adapted cultivars (Annicchiarico et al. 2011). Moreover, new lines of Portuguese subterranean clover (*Trifolium subterraneum* L.), a self-reseeding annual species, are available. Either lucerne or subterranean clover and perennial grasses are associated in traditional forage mixtures grown over large areas in temperate regions, particularly in southern Australia. Indeed, in the Southern Great Plains of the USA where severe summer drought is common, mixing summer-dormant tall fescue either (1) with lucerne under the right sowing design or (2) with annual medics (*Medicago* sp.), enabled the maintenance of adequate stand density and persistence of both species (Malinowski et al. 2011, Malinowski and Pinchak, 2015). Complementarity between grasses and legumes under rain-fed conditions requires further investigation to provide innovative mixtures for a range of environmental conditions.

## Towards new drought-tolerant cultivars of perennial grasses

Current research programs aim to develop a range of innovative, highly drought-resilient and water efficient cultivars of perennial grasses from Mediterranean germplasm and from crosses with temperate elite material by incorporating the summer dormancy trait. These new cultivars should provide rain-fed forage crops for Mediterranean areas subjected to increasing aridity and desertification risk and therefore will reduce the vulnerability of farming systems to climate change. Based on the remaining rich biodiversity in perennial grasses already collected in Mediterranean areas, it will add value to the summer dormancy trait that is endemic in this region. The aim is to select plant material adapted to severe summer drought but productive during the cooler rainy season thus enhancing the resilience of farming systems to climate change. In addition, seed productivity should also be improved in order to meet the demands of the seed market. Opportunities to use these cultivars also extend to temperate areas, in particular in Europe, where they can be used in breeding programs for improving adaptation to moderate drought.

Cocksfoot is the fourth most widely used grass genera of forage crops in the world (Bondesen, 2007) and thus appears to be a "model perennial grass". Moreover, this species is very widespread with ecotypes found from Northern Africa expressing complete summer dormancy to temperate northern Europe (Fig. 1).

*Figure 1*
*The perennial grass* Dactylis glomerata *L. has a large intra-specific variability including Mediterranean ecotypes with complete summer dormancy conferring an exceptional survival under severe drought*

The three main current research objectives are as follows: first, to create and select innovative plant material based on the analysis of linkages among the key traits, including summer dormancy, phenology, biomass production, and seed production. This will define the best trade-offs between traits across a range of ideotypes through the analysis of the genetic basis of these traits (Kallida et al. 2016). Second, to identify the environmental control of induction of summer dormancy since a clearer understanding of the role of photoperiod, temperature and water deficit is needed to predict the ideotypes best suited to local environments and to provide key knowledge for improving pasture management (sowing and defoliation stage, etc.). Third, to test the most promising lines/ cultivars of cocksfoot in association with companion legumes since under increasing drought, species mixtures combining both Mediterranean grasses and legumes should improve multi-annual productivity of forage crops through greater water and nitrogen use efficiency as well as long term drought resilience.



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# Adaptation of Mediterranean fruit tree cultivation to climate change

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## Context

Ongoing changes are currently affecting and will continue to affect most climate components (IPCC, 2014). Increases in temperature and soil salinity and decreases in water availability are the main changes that threaten fruit tree cultivation in the Mediterranean area, where more frequent extreme temperatures and drought episodes are expected. Considering the long periods required for fruit tree selection, orchard installation and cultivation, global change consequences do not appear to have been sufficiently taken into account in the fruit tree industry, given the high vulnerability of the sector (Dingkhun *et al.*, 2013). Since open field cropping systems largely prevail, fruit trees cannot escape the adverse conditions and must face, most of the time, the combined effects of elevated temperature and air drought during the leafy season whereas mild winter may affect the dormancy period of temperate species.

A range of fruit tree species are currently cultivated in the Mediterranean area with varied uses: fresh fruits (Apple, Peach, Apricot, Citrus, Fig); dry fruits or nuts (Apricot, Fig, Dates, Almond, Pistachios) and oil (Olive). Despite their different adaptation capacities, likely linked to their geographic origin, all these species will have to face the consequences of climate change: production losses, financial losses for the growers and a possible shift of growing areas. In the following, we exemplify some of the impacts due to climate changes and known physiological responses, and explore perspectives for possible adaptations and opportunities that could emerge from breeding or new species and cultivation methods.

## Abiotic constraints and physiological tree responses

Temperature is the main climatic factor affecting fruit species – impacting their physiology and yield either during the vegetation cycle or during the winter dormancy period (from autumn to spring). Higher temperature increases the leaf-to-air vapor pressure deficit and this in turn increases tree water consumption. Even in irrigated orchards, heat waves associated with dry air accelerate water loss by transpiration, which can exceed the intrinsic tree hydraulic conductivity in xylem and leaves, particularly when transpiration is poorly regulated by stomatal closure. This may lead to cavitation of xylem vessel (i.e. the rupture of the sieve stream), associated with low stem hydric potential. In these circumstances and upon the loss of turgor, some organs (leaves, twigs, fruits) or even the whole tree can die. On the contrary, transpiration can be limited by leaf stomatal closure (avoidance strategy) but this limits leaf photosynthesis and can lead to heat stress, since leaf temperature is no more regulated by the efflux of latent heat resulting from transpiration. The elevation of leaf temperature (>40 °C) can also affect the photosynthetic machinery. All these stresses limit biomass accumulation, i.e. vegetative and fruit growth. They directly hamper tree yield and may indirectly impact the development of future flower buds, through depletion of carbon reserves at autumn and during winter. A subsequent reduced tolerance to pests can also be observed.

Since fruit trees mostly have a C3 carbon cycle, the most favorable temperature for photosynthesis ranges from 25 °C to 35 °C. In apple, an optimum carbon balance (net photosynthesis minus maintenance respiration costs) is reached at a lower temperature than the optimum for photosynthesis, peaking at ca. 25 °C. In response to extreme temperatures (>40 °C), leaves display some plasticity through medium-term adaptation, e.g. synthesis of heat shock proteins. As the orchard annual yield results from a combination of instantaneous carbon budget with the duration of carbon assimilation from bloom to fruit harvest, the use of temperature-sensitive models can be helpful to predict the effect of general temperature rise.

Changes in temperature regime also impact the winter dormancy period. In temperate fruit trees, warmer air temperatures from autumn to winter may delay the dormancy break (chilling requirement), also delaying flowering time, whilst warmer spring temperatures may hasten bud break (heat requirement) and accelerate flowering. Subsequent impacts include floral abnormalities, flowering asynchrony of cross-pollinating cultivars and extended periods of the blooming phase, which may lead to poor fruit set (Atkinson *et al.*, 2013). Impacts on flowering phenology and their consequences on production (spring frost, poor pollination, extended fruit maturity, etc.) are particularly expected in the Mediterranean area. They reveal mostly vulnerabilities but also opportunities, according to regional and species differences (vulnerability to spring frost in altitude vs. poor frost risk at lower elevation).

### Box 1
### Impact of climate change on the phenology and fruit production in olive tree

Olive flowering time is considered as a reliable bio-indicator of Mediterranean climatic variations. Several studies have revealed a flowering advance in the olive tree as a consequence of increased temperatures. The flowering duration (the delay between the beginning of flowering and fruit set) of some varieties of the Menara olive collection (Morocco) was reduced between 1975 and 2015-2016. Moreover, olive trees located in the northern part of the Mediterranean exhibit the greatest heat requirement for floral bud development while those located in the warmest winter areas (southern Mediterranean areas) have a more rapid floral development. In the latter case, lower heat requirements probably result from an adaptation to warmer regions.

Observations have been conducted on the worldwide collection (WOGB Marrakech, 663 Mediterranean olive varieties with 4 tree replicates) since 2014 to extend the comprehension of chilling requirements and climate impact on flowering time in the olive tree. Flowering intensity per tree is also subject to visual estimation and qualitative assessment. Based on the temperature data (especially the number of hours of temperature ≤ 9 °C during December-January) for consecutive years, the flowering intensity between and within varieties is currently being analyzed. Preliminary observations suggest that insufficient chilling may directly impact flowering intensity. Moreover, a survey of four olive farms with a high intensive system near Marrakech in 2016 showed some production reduction with respect to expected values, which may result from a warmer winter temperature and reduced flowering intensity compared to 2015. In the arid Mediterranean area, considering the current climate change, the selection of more early flowering olive varieties (with low chilling requirement) thus appears as a priority to ensure olive productivity and regularity under warmer and drought conditions.

## Effects of high temperature on fruit yield and quality

As many processes occur at cell and tissue levels, most reproductive development events are impacted by high temperature. Protective adaptations are triggered against thermic stress but with detrimental effects on the primary metabolism, limiting the fruit yield. Beyond the increase in respiration costs, these effects notably concern the duration of the bloom-to-fruit maturity period, with hastened fruit maturity. In stone fruits, a shorter bloom-to-harvest period negatively impacts the potential fruit size, since carbon acquisition is shortened and not compensated by a better carbon influx. Fruit texture and shape can also be affected: after a shortened cell multiplication phase and increased individual cell growth, apple fruits, for example, are less dense and crisp. At harvest maturity, the malic respiration rate is stimulated by warm temperatures, with detrimental effects on the fruit acidity to sugar ratio. Moreover, the scarcity of cold night temperatures delays the onset of red-skin apple pigmentation by anthocyanins. Finally, diverse effects on fruit post-harvest have been noted, for instance in apples, where sunburn is enhanced by warm temperatures and high irradiance in the field. Skin blemish is generally observed, lowering the commercial value at harvest.

## Possible climate change adaptations for Mediterranean fruit trees

Natural adaptation of species to afford and/or withstand non-optimal climate conditions relies on a series of morphological and/or physiological processes caused by avoidance and tolerance strategies. Heat avoidance can result to a certain extent from leaf pubescence, which increases leaf reflectance, and/or from leaf lamina inclination, but the plasticity of these traits in response to heat is poorly documented in fruit crops. Adaptation may also involve the co-evolution of each species with its biocoenosis and cohort of predators, pollinators, etc. (see the Fig tree case below).

Regarding phenology, the negative consequences for fruit tree production could be reduced or even nullified by adapting the heat requirements of varieties to temperature changes at regional scale. However, in temperate species characterized by winter dormancy, the varietal adaptation of chill requirement and its interaction with heat requirement is complex and will require deeper knowledge of the signals and mechanisms linked to bud dormancy and growth (Cooke *et al.*, 2012). Bud rehydration which plays a key role in the transition from endodormancy to ecodormancy, may also trigger winter dormancy break. The modeling of fruit tree flowering time in diverse climatic regions has shown that warming impacts and likely adaptations greatly differ between species and cultivars. According to the RCP4.5 et RCP8.5 scenarios of the Intergovernmental Panel on Climate Change (IPCC), some species show limited risk at all sites across South Australia up to the year 2090 whilst others show greater risk both historically and in the future. As a complement to model-based predictions, breeding strategy, based on genetic determinism of bud phenology, is likely to create new opportunities for fruit trees facing temperature increase.

### Box 2
### Pollination in the Fig trees
### and possible changes in varieties

The Fig tree is characterized by substantial diversity of local varieties, mainly present in limited areas such as north Morocco. Fig varieties differ by their fruits reaching maturity without pollination ("Common type") mainly present in north Mediterranean areas or requiring pollination for fruiting, more suitable for drying ("Smyrna type") and present in south Mediterranean areas. This is probably linked to the associated pollinator, *Blastophaga psenes* L. which, despite its presence, does not have a sufficient population dynamic to ensure regular pollination in the north, whereas the inverse is observed in the southern Mediterranean areas. Under warming conditions, the population dynamics of the pollinator may be disrupted, leading to a dramatic loss of fig production of "Smyrna" varieties. It is expected that plant material will evolve in favor of "common type" varieties and hence in product uses from dried to fresh fruits.

In terms of the trade-off between carbon gain and transpired water, considering various climatic scenarios and the cost and/or availability of water resources for irrigation, increasing attention needs to be paid to the water use efficiency (WUE) of fruit trees, i.e., the ratio of biomass produced by water transpired over a crop cycle. Although increased WUE is generally desirable, the benefits of high WUE appear in very dry environments only. Moreover, thermoregulation resulting from transpired water plays a part in alleviating heat stress. Until recently, fruit breeding programs did not consider tree water economy as an important trait. Providing fruit growers with reliable information on variety behavior, in response to heat or drought stress, will be of increasing value (e.g. Virlet *et al*., 2014). Moreover, the choice of drought-resistant rootstocks is justified in semi-arid environments, but the selection of scion cultivars able to withstand sub-optimal conditions (heat waves, air drought, lower irrigation, soil salinity, etc.) without prejudice to yield will become more relevant.

### Box 3
### Screening for new rootstock selection: the example of Citrus

Citrus are grown on the various coasts of the Mediterranean basin where they represent almost 17% of world production. Spain, Morocco and Egypt are the main producers. Oranges, small citrus such as clementines, limes, lemons and grapefruits are the main varieties. Citrus production requires irrigation during summer: nearly 80 liters of water are consumed by a tree to produce an orange. In the southern Mediterranean area, deep boreholes for agriculture led to lowering of groundwater levels and increase of salt contents in irrigation water. Citrus are extremely sensitive to salt stress, especially grapefruit and orange.

Citrus are grown grafted on rootstocks that allow the tree to withstand many diseases (e.g. Tristeza or Phytophthora), but also confer tolerance to drought, salt stress or calcareous soils. The adaptation of citrus to salinity requires rigorous management of cultural practices: tree age, rootstock, grafted variety, irrigation systems, soil type and climate being the main factors that may modulate the stress impact. In addition to improved irrigation practices to limit the extraction of salts from the soil, rootstocks are required to limit the absorption of Na+ and Cl- in roots and limit their impact on the canopy, since these ions may be transferred passively into the transpiration stream through the xylem.

As with grapes, Cl- is responsible for chloroses leading to growth stop and reduction in fruit production. Leaf Cl- content is thus a good criterion to evaluate the tolerance/sensitivity of seedlings to salt stress. Poncirus (trifoliate orange) cultivars are of potential interest since they are tolerant to Tristeza, but they do not limit Cl- absorption in roots and transfer these ions to the aerial part. Rootstock cultivars such as Cleopatra or sour orange that maintain toxic ions in roots are the most suitable for adaption to salt stress.

However, such cultivars are susceptible to Tristeza. The current strategies are therefore (i) to select hybrids combining tolerance to Tristeza and salt stress; (ii) to create tetraploid genotypes that may confer tolerance to salinity. Some spontaneous tetraploids may be present among seedlings, and studies at the research institutes CIRAD in France and IVIA in Spain have shown that such rootstocks are more tolerant to salt stress and water deficit than the respective diploids. Other studies suggest that tetraploids have better capabilities of toxic ion compartmentalization and detoxification systems compared to diploids. Even though the impact of salt stress in orchards where tetraploid rootstocks are used remains to be fully explored, selecting varieties with appropriate physiological and molecular mechanisms is likely to limit the impact of toxic ions in the leaves. The use of tetraploids hybrids of Poncirus and Cleopatra mandarin as rootstocks in combination with varieties selected for fruit quality and less salt sensitivity thus seems promising.

# Innovative cropping systems for warm and dry conditions

Presently, the agronomical performance of intensive orchard depends on the satisfaction of water requirements, particularly during periods of active fruit growth. In this context, the water economy mainly relies on irrigation scheduling, and possibly regulated deficit irrigation (Steduto *et al*., 2012). In pip fruits, netting over orchards has been developed, either for protection against hail or pests (e.g. codling moth in apple) or to influence the microclimate: trees receive 10 to 15% less solar radiation and have a lower evaporative demand, since extreme temperatures and high vapor pressure deficit are avoided. This is globally beneficial if the fruit quality is maintained. Cultural practices based on the use of reflective sprays have also been developed for the protection of fruits, limbs and trunks, and evaporative cooling through overhead sprinkling to mitigate heat periods. In addition, experimentations on the potential benefit of associated crops or on traditional agro-systems experienced between the tropics and in southern Mediterranean areas, where species are often mixed or in multi-layers, could represent new solutions. In extensive cropping conditions, such as traditional rainfed fig or olive groves, soil water deficit cannot be avoided during the dry season, but it can be overcome by the capacity of root systems to explore deep soil layers and/or low planting density which increases access to water for each tree. The relative benefit of intensive / traditional / associated crops / multi-layer cropping systems will certainly have to be further evaluated in the light of climate change and regional priorities.

# Conclusion

The risks and adaptation strategies of Mediterranean fruit trees to climate change depend on the species, its intrinsic ability and plasticity linked to its original geographic area, and its ecotype, but also on fruit use (e.g. fresh/dry/oil) and storage possibility. Many adaptation options can help address climate change impact, but no single option is sufficient by itself. We therefore recommend combining several approaches, notably breeding for new material and innovative cropping systems. While the ongoing global warming threatens fruit tree industry all around the Mediterranean Sea, it also opens new challenges and opportunities for renewing plant material (scions and rootstocks) and cropping systems. Some fruit species from tropical dry areas could perhaps be considered for the diversification of cultivated fruit species around the Mediterranean Sea, thus creating new opportunities. Biologic and agronomic options will also have to be complemented by measures for accompanying populations, especially the poorest and most fragile, in order to balance inequalities and contribute to social stability, taking into account the resilience of farming structures and the proximity between growers and consumers.



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# Climate change and dependence on agricultural imports in the MENA region

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## Introduction

The Middle East – North Africa (MENA) region, which is geopolitically complex and highly strategic, is characterized by a high level of dependence on agricultural imports, which currently account for 40% of its food needs. Over the last five decades, demographic growth and changes in dietary habits have led to a marked increase in food requirements. Although regional agricultural production has increased substantially over the same period, it has been unable to keep pace with the increase in demand, partly because of the soil and climate constraints and also because of limitations in terms of agricultural policy. Regional dependence on agricultural imports is likely to continue to escalate in the foreseeable future, as a result of ongoing demographic expansion and changes in eating habits, as well as of climate change impacts in a region recognized as a climate "hot spot". Agricultural imports place a significant burden on state budgets, and agri-food policies in the region continue to struggle with urban and rural poverty. In this context, it is important to understand which factors within the regional agri-food system are most likely to contribute to – or, on the contrary, might help mitigate – a continued increase in agricultural import dependence. In this study, we analyse two scenarios for the region through 2050, taking into account the anticipated effects of climate change. These scenarios were simulated using a biomass balance model. Simulation results suggest that dependence on agricultural imports is likely to continue to increase in the region, with climate change as a major contributing factor.



## Agricultural imports cover 40% of regional food requirements and are increasing rapidly

The MENA region is notable both for its high percentage of arid and semi-arid lands, characterized by low agricultural productivity, and for its rapid demographic expansion, with a population that has increased by a factor of 3.5 in fifty years – from 139 million inhabitants in 1961 to 496 million in 2011. A key challenge for the region lies in its ability to meet its food needs. It is to highlight this situation that we have undertaken a study on the agro-food system of the MENA region through 2050 (INRA, 2015; Le Mouël et al. 2015).[1]

While demand for agricultural products increased sixfold from 1961 to 2011 in the MENA region, as a result of population growth combined with a pronounced nutritional transition, the domestic supply rose only fourfold, partly due to the region's severely limited land and water resources.

As gains in agricultural production have failed to keep pace with rising food requirements, the imbalance has been made up by increased reliance on international markets to meet domestic requirements in food and feed: net dependence on agricultural imports has increased from 10% to 40% in fifty years, with significant variation among sub-regions (Fig. 1). Between the

1. This study was conducted by the INRA (i.e. French National Institute for Agricultural Research) with the support of Pluriagri, an association of representatives of some commodity sectors (including Avril, the French Confederation of Sugar Beet Producers, and Unigrains) together with Crédit Agricole S.A., supporting foresight studies of agricultural markets and policies. Scientific coordination was provided by Chantal Le Mouël and Bertrand Schmitt (INRA). A working group including both scientific experts and stakeholders was given the task of building the scenarios and discussing the results: S. Abis (CIHEAM), C. Ansart (Unigrains), P. Blanc (Bordeaux Sciences-Agro and Sciences Po Bordeaux), X. Cassedanne (Crédit Agricole), R. Cuni (CGB), J.-C. Debar (Pluriagri), P. Dusser (Avril), H. Guyomard (INRA), F. Jacquet (INRA), Y. Le Bissonnais (INRA), M. Padilla (CIHEAM-IAMM), M. Petit (FARM), P. Raye (CGB France) and G. Regnard (Crédit Agricole).

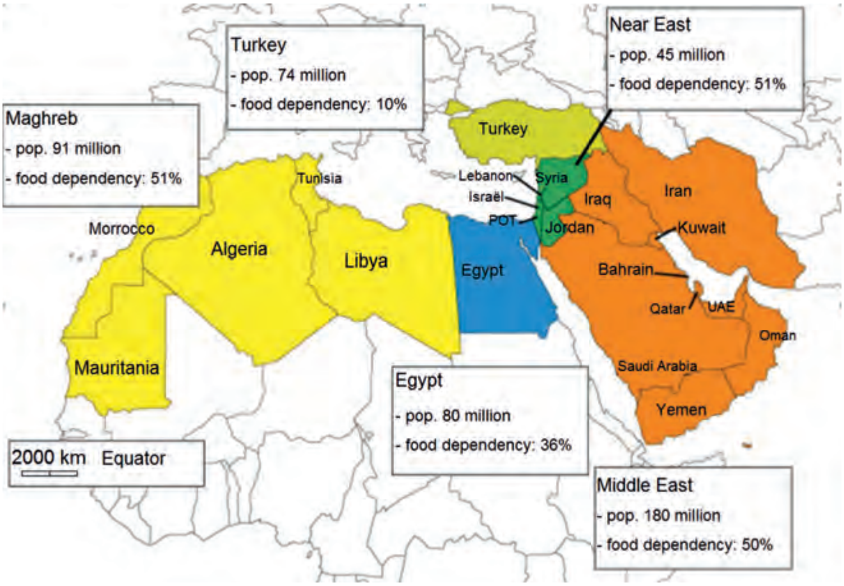


*Figure 1*
*The MENA region and its sub-regions.*
*2011 data; "pop"= population; "food dependency" = dependence on imports (% of net imports in total domestic consumption, expressed in kilocalories).*

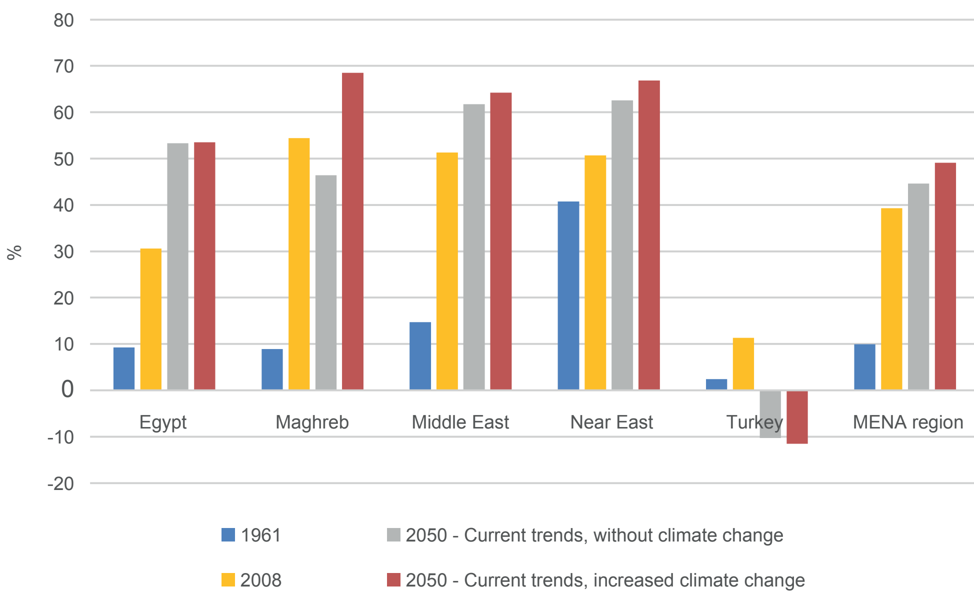


*Figure 2*
*Agri-food net import dependence of the MENA region and its sub-regions in 1961, 2008 and in 2050 for the scenarios "Current trends (in population growth, dietary habits and agricultural production), without climate change" and "Current trends with increased climate change" (% of net imports in total domestic consumption, expressed in kilocalories).*

Box 1
The GlobAgri-Pluriagri model

GlobAgri is a database and quantitative modelling tool developed by both INRA and CIRAD to analyze the use and availability of agricultural resources at global and regional levels. Using the FAOStat database and various sources of complementary data, GlobAgri-Pluriagri divides the MENA region into five sub-regions (Fig. 1) and the rest of the world into 12 regions. For each of these regions, the model establishes a biomass balance for 36 agricultural products in which, for each product, domestic production plus net imports (imports minus exports) equals the sum of uses for human consumption, animal consumption, and other uses, plus losses (mainly associated with processing phases) and stock variations. As the model does not include economic variables and production and consumption do not adjust according to the economic behavior of producers and consumers, consumption levels are determined in advance by the modeller, along with certain production factors such as crop and livestock yields. Adjustments determine the levels of imports, exports, and domestic production necessary to achieve equilibrium between resource availability and resource use. To this end, two constraints are introduced: the first ensures that, at the global level, the sum of imports equals the sum of exports for each product; the second imposes a maximum cultivable land area for each region. When the limit on cultivable land area is reached, equilibrium is achieved by reducing exports (i.e. the world market shares of the region) and/or increasing imports (i.e. the coefficients of import dependence). In the case of the MENA region, the model does not adjust exported quantities, because of the specificity of the production types involved (mainly fruits and vegetables).

beginning of the 1960s and the end of the 2000s, the Maghreb and the Middle East saw their dependence on agricultural imports increase from 10 to 54% and from 15 to 50% respectively. In the Near East, where this dependence already stood at 40% at the beginning of the period, a similar level of around 50% was reached by the end of the 2000s. Egypt shows lower levels of agricultural import dependence, but nevertheless rose from 10 to 30%. Turkey is the exception within the region, with a historically low agricultural import dependence that has reached 10% only in the past few years.

## Under current trends the agricultural import dependence of the MENA region will continue to rise through 2050

We used the GlobAgri-Pluriagri model (see box 1) to simulate the effects of projecting current trends of the various components of the MENA agri-food system through the year 2050 ("Current trends without climate change" scenario) on the regional agricultural import dependence.

In the MENA region as a whole, improved yields up to 2050 in the crop and livestock sectors would not be sufficient to compensate for rising food needs. Because of the constrained cultivable area, the imbalance between domestic supply and demand would be made up by increased agricultural imports, resulting in rising regional import dependence, from 40% in the initial (2008) situation to 45% in 2050.

This regional average masks contrasting situations depending on the sub-region. Egypt, the Middle East and the Near East would experience a substantial increase in their import dependence, from 30 to 53%, from 51 to 62% and from 51 to 63% respectively. In the Maghreb and Turkey, domestic agricultural production would expand faster than domestic demand, enabling both sub-regions to reduce their import dependence level between 2008 and 2050 (Fig. 2). In the Maghreb, import dependence would decrease from 54 to 46%, while Turkey could even become a net exporter of agri-food products, with import dependence shifting from 11 to -10%.

## Climate change will contribute to increase agricultural import dependence in the MENA region, especially in the Maghreb

The Fifth Report of the IPCC states with growing confidence that both the magnitude and the impacts of climate change are likely to become more severe in the coming decades (IPCC, 2013). The scientific literature agrees, moreover, that the MENA region will potentially be one of the most heavily affected regions, in particular its Maghreb sub-region (IPCC, 2013; Hare et al. 2011, Niang et al. 2014).

To address these potentialities, we considered the most extreme case projected by the IPCC, corresponding to a radiative forcing of 8.5 W/m² (RCP-8.5). This assumption corresponds to the probable outcome if international agreements and mitigation policies used for addressing climate change are unable to slow the global processes currently underway. According to the available literature (Müller and Robertson, 2014; Zabel et al. 2014), we adjusted the hypotheses on crop yield growth and on maximum cultivable areas relative to the "Current trends without climate change" scenario. In the resulting "Current trends with increased climate change" scenario, crop yields in 2050 are between 10 and 20% lower than in the previous scenario.

Regarding cultivable land, the Maghreb would be the most affected sub-region, losing close to half of its cultivable land area between now and 2050. The Near

East would also be strongly impacted, losing a quarter of currently cultivated area. Cultivable land area would remain unchanged in the Middle East. Given its distinct geography (a more northern position, mountainous areas, more favourable hydrography), Turkey could experience a significant increase in cultivable land area, amounting to 15% of currently cultivated land.

As we assume continued availability of water for irrigation, yields and cropping areas remain unchanged for irrigated agriculture. As a result, our "Current trends with increased CC" scenario leaves Egypt unaffected relative to the previous scenario (Fig. 2).

The severe deterioration of the conditions of agricultural production in the Maghreb would result in a sharp increase in its dependence on agri-food imports, increasing to 68% of domestic consumption by the year 2050 (Fig. 2). The increased dependence on agricultural imports in the Middle East and Near East sub-regions would also be aggravated, with import dependence now reaching 64 and 67%, respectively.

Within this rather bleak overall picture, Turkey once again appears to be the exception, with the beneficial impacts of climate change in terms of cultivable land area compensating for the negative impacts in terms of yields. This country could slightly strengthen its position as a net exporter of agri-food products in the "Current trends with increased CC" scenario, relative to the previous one.

## Conclusion

Current trends in population growth, dietary habits and agricultural production would lead to a continued rise in agricultural imports in the MENA region through 2050. Increases in agricultural import dependence would be more pronounced as the impacts of climate change are felt in the region. The three sub-regions of the Maghreb, the Middle East and the Near East would be most strongly affected, with net imports reaching up to almost 70% of domestic requirements.

The economic, social and political risks of reaching such elevated levels of agricultural import dependence are well known: trade imbalances, increased national public debts, strong exposure to global market fluctuations, recurrent food crises, increasing poverty, etc. Slowing this rise in agricultural import dependence is thus imperative.

There are several ways of reducing the burden of import dependence in the MENA region, such as stimulating agricultural production through technical progress that would improve both crop and animal yields; or regulating food demand by changing food diets; or reducing food waste and losses along the food supply chain[2]. Nevertheless, given that regional agricultural import dependence will become more pronounced as the impacts of climate change become more severe, the most effective means of limiting import dependence is to take steps to mitigate climate change, which only international agreements and the adoption of vigorous global climate policies would make possible.



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2. All these alternative options are investigated in the study conducted by Inra with the support of Pluriagri, which considers a set of additional scenarios (such as "Technical progress", "Mediterranean diet", "Reduced waste and loss", for instance), not presented here due to space constraint. All these scenarios and their results are available in INRA (2015) and Le Mouël et al. (2015).

Chapter 3

# Local knowledge, scientific knowledge and food security in the Mediterranean region

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## Abstract

Intricate linkages between climate change and socio-political dynamics in the Mediterranean region may give rise to new risks for crops and food security. As one of the world's biodiversity hotspots, the Mediterranean is also a major cradle of domestication and harbors a vast array of wild crop varieties and traditional landraces. We examine various situations in which local historical knowledge configures landscapes and produces agro-biodiversity – living matrices incorporating nature and culture and contributing to the history of the Mediterranean region.

These landscapes are suffering from urbanization and inappropriate public policies that overlook the importance of local farmers' knowledge. This chapter aims at evaluating local practices within a set of agroecosystems and their inputs to secure food security within the context of climate change.

The following cases are analyzed: (1) the use of wild olive (oleasters) grafted with olive varieties to create biological heterogeneity – an old technique perpetuated by farmers in northern Morocco and currently being replaced by large scale monoclonal olive plantations; (2) the ongoing taming of interactions between the Black truffle, their host trees and companion plants managed by truffle growers – currently under ecological experimentation; (3) the secular domestication of the Argan tree and associated bee keeping, favoring diversity through the engineering of differentiated spaces and protection of rich nut diversity – the latter is now marketed for the cosmetic industry; (4) locally differentiated bee populations in Cévennes in France, linked to local practices, and undergoing threats due to changes in practices and hybridization with imported bee populations.

The models described form part of a framework of biocultural and spatio-temporal interactions which it is now essential to understand. Above all, the situations described all bear within them key ideas for a more joined-up relationship between local and scientific knowledge.

## Résumé

Les effets conjoints du changement climatique et des dynamiques sociopolitiques accroissent les risques sur les espèces cultivées et la sécurité alimentaire en Méditerranée. *Hotspot* de biodiversité à l'échelle mondiale, cette région est également un des berceaux de la domestication ; en outre, la région comporte de nombreux parents sauvages ainsi qu'un grand nombre de cultivars et de races traditionnelles. Nous examinons diverses situations illustrant le rôle des savoirs locaux historiques dans la configuration des paysages et de l'agrobiodiversité – des matrices vivantes incorporant nature et culture et ayant contribué à l'histoire de la région. Ces paysages souffrent de l'urbanisation et de politiques publiques ne prenant pas en compte l'importance des savoirs agricoles locaux. Ce chapitre évalue les pratiques locales dans une série d'agroécosystèmes et leurs apports à la sécurité alimentaire dans un contexte de changement climatique.

Nous abordons les cas d'étude suivants : (1) l'utilisation de la diversité biologique d'oliviers sauvages (oléastres) greffés par des variétés d'oliviers, une ancienne technique perpétuée par les paysans du nord du Maroc et en cours de remplacement par des plantations d'oliviers monoclonaux, à une large échelle ; (2) l'apprivoisement en cours de la Truffe noire, de son arbre hôte et de ses plantes compagnes par les trufficulteurs ; la gestion des plantes compagnes fait désormais l'objet d'expérimentation en écologie ; (3) la domestication séculaire de l'arganier associée à l'apiculture, favorisant la diversité à travers la différenciation des espaces et la protection d'une riche diversité de noix ; cette dernière est en forte demande pour l'industrie cosmétique ; (4) la différenciation

des populations locales d'abeilles dans les Cévennes en France, en lien avec des pratiques locales menacées par des changements de pratiques et l'hybridation avec des populations d'abeilles importées. Tous les modèles décrits font partie d'un cadre spatio-temporel et d'interactions bioculturelles qu'il est désormais essentiel de mieux saisir. Surtout, les situations décrites comportent toutes des idées clés pour une meilleure synergie entre savoirs locaux et savoirs scientifiques.



# Introduction

Agricultural practices keep evolving, both because of social changes and the recomposition of various regions, and thus need to adapt to climate change and the sustainable management of resources, including biodiversity and water, to the increase in population and the emergence of new risks for crops.

Local knowledge is now at the heart of environmental issues; it is recognized by the Convention on Biological Diversity (CBD, Earth Summit, 1992), the Aichi targets (Nagoya CBD, 2010) and Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES, 2015).

In the Mediterranean region, the gap between coastal urbanization and the hinterland exemplifies contemporaneous territorial dynamics, which lie at the origin of new links between urbanized areas, active agricultural areas, and less active areas (grazing areas, extensive crops, etc.) and "natural" areas (forests, wetlands, lagoons, etc.). The appeal of "modern" lifestyles, definitive or temporary migrations, the emergence of new social and economic inequalities, tensions of an agriculture that expresses divergent interests, ecological interactions, and water flows between these different territorial areas constitute issues which are either poorly controlled or insufficiently addressed by public modes of action.

The links between scientific knowledge and local knowledge requires that the latter be fully considered – no easy matter for entire swathes of human know-how that have often been sidelined, especially in the early 20th century with the advent of agricultural modernization and the foregrounding of an agricultural production paradigm based on specialization and improved varieties – all based on massive inflows of chemical inputs – which failed to take account of biodiversity and ecological processes. This agricultural model is now highly debatable in light of the environmental crisis we are experiencing on a global scale, particularly related to the impact of modern agriculture on greenhouse gases, energy issues (oil needed to produce chemical inputs), emissions and therefore climate change.

The deficit in agricultural production raises issues related to the farming systems and food of the people of the Mediterranean that will be considered over the long term (drawing on archaeology, history and environmental archaeology). They enable scenarios to be developed for the management of natural resources in the long term, and for changes and the human impacts of biodiversity from a sustainable development perspective. Farming systems – an example of sustainability – are considered from an agro-sylvo-pastoral point of view and as a complement to the fishery environment.

The Mediterranean, one of the world's cradles of domestication, can help us reflect on the interactions between human societies and the environment, because of its role both as a biodiversity hotspot and as a place where human societies have interacted with nature since the Neolithic. The Mediterranean paradox (Biodivmex Mistrals, http://biodivmex.imbe.fr/) lies in the fact that Mediterranean agricultural landscapes have long nurtured Mediterranean societies, while retaining a large part of their biodiversity.

This chapter examines various situations in which local historical knowledge in the Mediterranean configures landscapes and produces agro-biodiversity – living matrices incorporating nature and culture and contributing to the construction of the history of these societies.

The questions raised are numerous and are located at the intersection of human activity, the biology of bees and their links to the territories, the complex interactions between truffles, their host trees and their companion plants, techniques for olive grafting onto oleasters that have been totally forgotten by science, and argan trees that have been domesticated and configured for millennia, and are now a key feature of the cosmetic industry. All the models described form part of a framework of biocultural and spatio-temporal interactions which it is now essential to understand. Above all, the situations described all bear within them key ideas for a more joined-up relationship between local knowledge and scientific knowledge.

# Grafted oleaster-olive agrosylvopastoral systems in Northern Morocco

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## Oleaster and olive, a long history of man-forest interactions

An average of 2.5 million tons of olive oil is produced annually at global level (COI 2015). Mediterranean countries from the EU and from southern and eastern Mediterranean regions still represent the major exporters. The amounts consumed in source areas are difficult to evaluate, although olive oil is a major element of local diets and health. Understanding the historical and cultural bonds and associated empirical knowledge developed over millennia between Mediterranean societies and oleaster (*Olea europaea*, var. *sylvestris*) and its domesticated form, olive (*Olea europaea*, var. *europaea*), is crucial to understanding the present and anticipating future scenarios.

The olive tree and its wild form, the oleaster, are indispensable companions of Mediterranean societies both for their high symbolism (e.g. Athena's olive tree associated with the foundation of Athens) and for material purposes for producing oil for light, food, esthetic purposes, medicine, fuel and construction wood (Kaniewsky et al. 2012). Oleasters were abundantly used in the Levant well before the advent of agriculture 19,000 years ago (Kislev et al. 1992). During the Neolithic, human groups in the Mediterranean developed swidden agriculture based on the use of fire and long forest fallows for cereal cultivation and pastoral activities around 8000 – 7000 BP. In Sicily, Tinner et al. (2009) identify an expansion of Olea trees 7300 -7000 BP, with a parallel increase in *Cerealia-Rumex*, *Chamaerops, Urtica* and *Ficus carica* and to the expansion of agriculture. This is potentially a form of proto-culture of *Olea*, as was also suggested by Terral and Arnold-Simard (1996) in Spain. Although tree domestication occurred after the domestication of cereals (Zohary and Spiegel Roy 1975), incipient forms of tree domestication were probably present very early in prehistorical times as well as being an ongoing contemporaneous practice (Aumeeruddy-Thomas et al. 2014).

Although olive domestication and cultivation was initiated in the East (Besnard et al. 2013), multiple domestication sites are found throughout the Mediterranean basin (Terral et al. 2004). The olive may have known different forms of exploitations and it has been suggested by Camps (1961), who studied Berber groups in northern Africa, that grafting oleasters was used extensively by Berbers before they were colonized by the Romans.

## Objective

In this paper we compare two distinct olive-based agroecosystems, their social-ecological characteristics and importance for food security. These are: 1) Historical grafted oleaster-olive agroecosystems found throughout the Maghreb, based on a case study conducted in northern Morocco in a sampled area in Ouezzane Province, 2) Modern olive plantations using microcuttings raised in nurseries and a range of techniques favored by new agrarian policies in the same zone. We analyze practices involved in their development, their distribution and spatial organization, diversity of food products; environmental factors including the topographic wetness index (TWI) based on a field numeric model (SRTM 2014) and the topographic position index (TPI).

The Rif borders the Mediterranean Sea to the north and is a region crossed by a mountain range that stretches from the Tangerine peninsula (west) to the frontier of Algeria (east). It is inhabited by three socio-linguistic groups, the Jbala (arabophone), the Ghomara and Berber Rifians (berberophone).

## Grafted oleaster-olive agroecosystems

Grafting is absent today in Northern and Eastern Mediterranean countries except in some islands such as Corsica, Sardinia, and Lesbos (Greece) where there are remnants of grafted olive orchards. The Romans are known to have started large scale olive plantations and developed plant breeding in nurseries (Brun 1996), an approach which may have eliminated grafting on wild trees. In the Rif, grafting oleasters was still very important in the 1970s (Fay 2015) and our observations show that farmers still graft wild oleasters in frontier areas between the forest and agroforests. If oleasters are not available, "feral" oleasters or escapees from cultivation are saved and transplanted, until they reach the size required to be grafted (Aumeeruddy-Thomas et al. 2014).

Farmers interviewed in this region unanimously consider that grafted oleaster trees are the most vigorous, produce more, and are less prone to be broken by strong winds or affected by dry climatic events. They are also widely known to produce oil which is much tastier. However, trees originating from micro-cuttings are seen as vulnerable, not productive, not durable and produce a less tasty oil, attributed by farmers to their lack of taproot system.

The construction of grafted oleaster-olive agroecosystems is driven by three major factors: a) customary land tenure systems, b) use over historical times of oleaster oil still highly prized in the Rif and, c) a sophisticated knowledge of grafting techniques. Grafting oleasters originating from the clearing of natural forests enables to acquire new agrarian properties because productive trees are an important marker of collectively recognized property. Similar systems are well-known in other regions such as in South East Asia. During the French Protectorate period (1912-1955), forests were registered ("cadastré") and access was restricted even for pastoral activities, although they represented important rangeland areas. This resulted in an accelerated rate of forest transformation and tree plantation in order to maintain access to the land (Fay 2015). Grafting oleaster thus represents a strategy for transformation of the forest into new stabilized agricultural lands.

The farmer clears the maquis by cutting all trees at the exception of some oleasters according to the density required. He then burns, sows cereals and grafts the oleasters. These fields progressively become permanent open savannah types of agroforests (Photo 1) including pasture lands based on a rotation between cereals, pulses and fallow periods. Livestock currently graze after the cereals have been harvested. Grafting is always conducted on large diameters (> 5 cm) and is exceptionally conducted directly on roots when the oleaster is too old. The scions chosen are a set of traditional olive variety but one clone, the Picholine marocaine, is dominant, as elsewhere in Morocco (Khadari et al. 2008). The top of the grafted oleaster is coated with mud mixed with cereal straws – a mixture currently used for many constructions in the region. These trees quickly start producing relatively significant quantities (20-50 kg after three years). The productivity of the tree is attributed by the farmers to the vigor of the rootstock.

The latter also influences the quality of the scion. In the words of some farmers, the variety changes its "passport", the association of the two parts giving a longer life span to the scion and better oil quality.

*Photo 1*
*Olive-Oleaster agroforests with cereal, hay production, broad bean fields in the forefront and uneven oleaster-olive tree populations throughout the landscape.*
*© Yildiz Aumeeruddy-Thomas, Ain Dorij, Maroc, 2014*

Some oleasters are never grafted because they are known to yield very large amounts of fruits and are differentiated into two categories, big olives (*berri meslal*) and thin olives (*berri rkek*). Both are brought to the mill when significant harvests are available and produce a highly prized medicinal oil, "*zit d'l berri*" (Aumeeruddy-Thomas et al. 2014).

Olive oil from oleaster – olive agroecosystems are extracted in traditional or modern electric mills. These mills are owned either by individuals or by larger enterprises. A diversity of oil types depends upon the extraction systems. They include in order of preference locally, *zit d'lma*, oil extracted without presses and strictly through decantation in water basins, *zit chamiya*, which is obtained from traditional pressing mats made from doum palm (*Chamaerops humilis)* and a mill using a grinding stone, and the *zit makina*, oil extracted from continuous systems in large industrial machines. The latter is the least appreciated because it requires hot water and high pressure but the rapidity of extraction is seen as an advantage. *Makina* oil is meant mainly for sales and export. Most families prefer the traditionally pressed oil which they think has the highest quality and the best taste.

Other products from oleaster-olive agroecosystems are cereals, mostly barley and a range of other cereals that are becoming increasingly rare such as rye (*Secale cereale*) and old wheat varieties, pulses including local landraces of lentils, chickpea (*Cicer arietinum, Kortchi*, *Maayzou* landraces), broad bean (*Vicia faba*, a major food and rotational crop), pulses specifically used to feed animals with many landraces of bitter vetch (*Vicia ervilia*) and vetch (*Lathyrus sativus*). Bitter vetch has almost disappeared throughout the Mediterranean. In the Rif it is currently grown on very poor soils (El Fatehi et al. 2014). All the pulses cited are nitrogen-fixing plants and therefore enrich the soil. Other tree species such as Caroub (*Ceratonia silique*) used as fodder and Figs (*Ficus carica*) a staple fruit throughout the Maghreb, are associated with traditional oleaster-olive agroecosystems. Such agroecosystems are also rich in adventitious herbs used currently as highly nutritive steamed salads (*bakoula*) in spring (Clochey 2014). Finally, highly diverse animal dairy and meat products are based on the breeding of small sheep flocks, cows and other domestic animals such as chicken. Mules also graze in this agroecosystem; they are important for work and transport.



## Modern olive plantations

Modern plantations are based on an aggregated system devised by the “Plan Maroc Vert” (PMV) the present agrarian policy of the Moroccan State supported partly by a bilateral project with USA, the Millenium Challenge Account (MCA). These policies and the associated MCA project have boosted the development of new olive plantations which require large aggregated perimeters of at least 500 hectares requiring that farmers form a formally registered economic group (GIE). Farmer’s lands are generally selected in the richest arable lands where people used to cultivate cereals associated previously with relatively low density of olives and other trees. These lands, once cleared, are managed by a large state-funded enterprise that hires workers for digging holes and planting high densities of olive plants (50 – 100 trees /ha) in an orderly way (lattice-square plantations with trees 10m apart). They also water and protect the young plants against thieves. Olive plants originate from micro-cuttings raised in nurseries in large towns such as Meknes. Only one or two varieties at a time are planted. These may be *Haouzia* and/or *Menara*, a variation that probably originates from somatic mutations of the Picholine marocaine (El Bakkali et al. 2013). In areas where water is not accessible, water is transported by lorries for irrigation. Workers are very rarely hired locally. Olive trees from these projects yield only 3 – 5 kilos after 5 years. For two years, farmers are not allowed to bring animals to graze because of the high risks for small plants. Although farmers may plant some cereal and pulses, the first 2 years represent a no man’s land for farmers.

Adventitious herbs are generally linked to cultivated cereals and pulses. The products from these new olive plantations are thus very low in quantity and do not contribute to local food security. The plantation density may in future overshadow cereals because of the high density unless farmers cut some trees after the two-year project period. Finally, oil originating from such plantations is extracted in large extraction units. In the area studied, one large production unit run by a farmer cooperative has machines that can produce 30 tons per day. At present the cooperative is experiencing the greatest difficulty because newly planted olive trees will not yield sufficient amounts for up to 10 years. Farmers therefore draw from their traditional olive plantations which in turn may decrease the individual access of each family to oil that is used directly because oil sold by cooperative aims to find larger outlets.



## Landscape structure and topo-hydrological factors

The two maps presented below (fig 1 and fig 2) show the two distinct situations that are compared. Table 1 shows associated topographic and water availability indexes that characterize them.

The oleaster-olive agroecosystems represent a complex landscape mosaic integrating small patches of forests, open areas of annual crop productions, new olive plantations as well as mixed grafted oleaster-olive (fig 1). The latter shows that farmers have not hesitated to renovate existing oleaster-olive plantations with new plants possibly originating from projects. Through integrating traditional and modern systems, farmers' strategies indicate their interest in renovating old grafted oleaster plantations and/or occupying land. Indeed, while doing other work in parallel, planting trees enables farmers to harvest and tend on a part-time basis or rent to a tenant and recover a portion of the harvest. Grafted oleaster coverage (23%) is similar to the 24% of annual crop coverage. The site is topographically higher in altitude and has the strongest slopes (TPI and slopes). New olive plantations and annual crop areas occupy the flattest areas. Maquis is non-appropriated land and its presence is difficult to interpret. The second site is less high in altitude and has lower values of mean slopes. Such areas are major target areas for PMV/MCA industrial plantations which represent 92% of coverage. The landscape homogeneity is much higher than in the first site. Access to soil water is not significantly different between the two sites or between categories within each site.

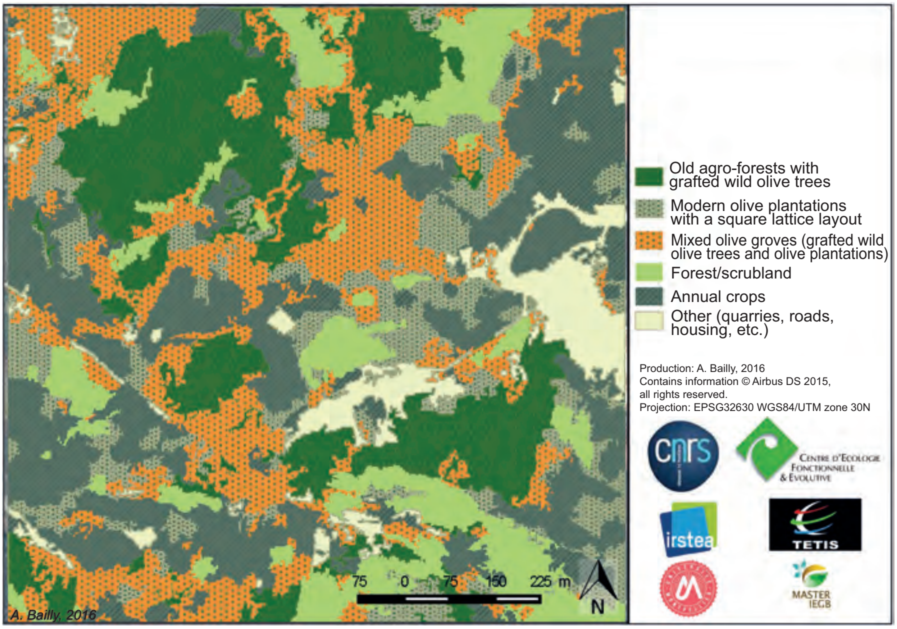


*Figure 1*
*Olive-growing in the province of Ouezzane:*
*example of a douar, the rural community of Mesmoda*

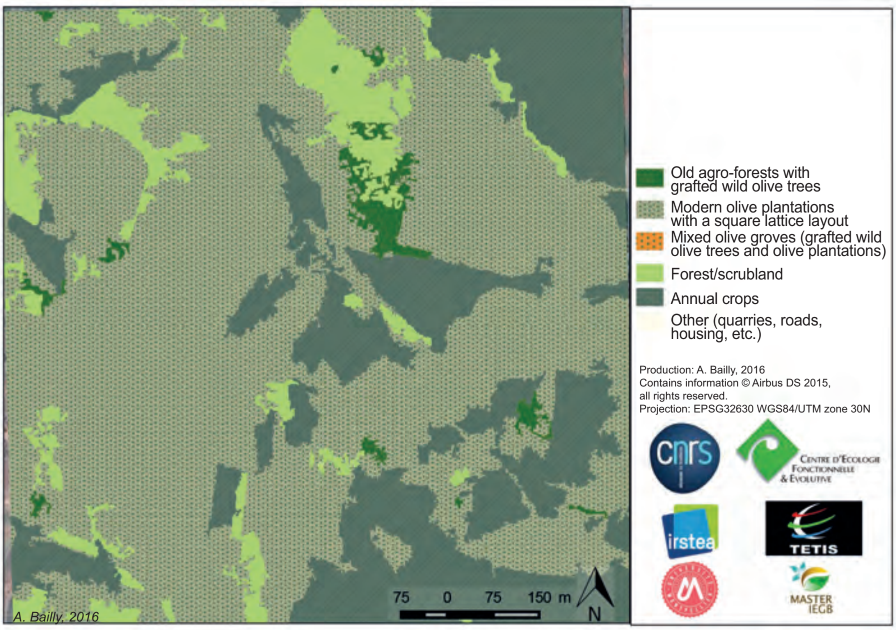


*Figure 2*
*Olive-growing in the province of Ouezzane:*
*example of a douar, the rural community of Bni Quolla*

*Table 1*
*Measures of environmental factors in each plantation class between the two types of olive agroecosystems.*

| Site | Class | Land Use | TPI mean | TPI stdev* | slope mean | slope stdev* | TWI mean | TWI stdev* | Area (%) |
|---|---|---|---|---|---|---|---|---|---|
| Mes | 1 | Grafted oleaster system | 0,2621 | 1,5750 | 16,2350 | 7,9193 | 7,1627 | 0,9965 | 23,20 |
| Mes | 2 | Modern plantations | 0,2314 | 1,2934 | 11,5370 | 6,1420 | 7,2237 | 0,9072 | 14,00 |
| Mes | 3 | Mixed systems | -0,2694 | 1,4045 | 10,9516 | 4,8307 | 7,6421 | 1,1373 | 20,50 |
| Mes | 4 | Maquis | 0,6788 | 1,3871 | 11,4485 | 5,0808 | 7,1939 | 0,9798 | 12,20 |
| Mes | 5 | Annual crops | 0,1255 | 1,2445 | 10,8070 | 6,1550 | 7,3188 | 0,9370 | 24,20 |
| Bni Quo | 1 | Grafted oleaster system | 0,1620 | 0,7511 | 10,3590 | 4,1603 | 6,9283 | 0,8530 | 1,90 |
| Bni Quo | 2 | Modern plantations | -0,0313 | 0,9928 | 9,3751 | 4,7584 | 7,3500 | 0,9999 | 62,90 |
| Bni Quo | 4 | Maquis | 0,2404 | 1,1039 | 9,8380 | 5,5106 | 7,0703 | 1,0970 | 8,90 |
| Bni Quo | 5 | Annual crops | -0,0762 | 0,8309 | 7,5873 | 3,5801 | 7,5280 | 1,0283 | 26,30 |

Mes: Mesmouda site, represents oleaster-olive grafted agroecosystem and other classes in a complex mosaic.
Bni Quo: Bni Quolla site, represents a large PMV/MCA project plantation area with a low landscape mosaic diversity. Indexes calculated with SRTM.
TPI: Topographic Position Index, calculated in Qgis with SAGA.
TWI: Topographic Wetness Index, calculated in Qgis with SAGA.

# Discussion and conclusion

This paper shows that grafted oleaster-olive agroecosystems, while being an ancient technique, offers much hope as a model for food security within a context of climate change. Farmers' capacity to take advantage of highly heterogeneous mountain terrain needs to be given the highest priority in future research. The vigor of the tree and the quality and taste of the oil is the main reason for farmers to maintain this technique because there is almost no forest left to transform. Grafting is scientifically acknowledged as having many positive impacts on domesticated crops (Warschefsky et al. 2016). In our case they allow the domesticated variety (mostly the Picholine marocaine) to have access to a large amount of nutrients from the rootstocks which are genetically very heterogeneous because they originate from a natural population. Rootstocks are known to be in contact with a soil microbiome made of a rich network of endophytic fungi in the case of *Olea europaea* and bacteria (Martins et al. 2016). These authors suggest that such associates may play an important role in production as well as protection against diseases through providing water and nutrients. Studies on other species show that specific types of genetic material may be transmitted between the rootstock and the variety (scion), a totally new research area which requires more investigation. Moreover, it is also known that the scion can also influence the biology of the rootstock because the litter is produced by the upper part of the tree which is transformed in the litter and feeds the rootstock.

From an environmental perspective, the complex landscape mosaic of the oleaster-olive agroecosystem corresponds to the "nature matrix" that Perfecto et al. (2009) described. The high level of biotic interactions and species diversity within such complex landscapes is likely to make such systems, highly adaptive in contexts of climate change as well as regarding sanitary risks. It is interesting to note that the major olive disease, a bacteria (*Xylella fastidiosa*) which currently affects olive in northern Mediterranean countries has not yet affected varieties grafted on oleasters in Corsica (Rasplus, personal communication, 2016).

The oleaster-olive agroecosystem is also by far more productive for local diets and food security. Industrial oil from new PMV/MCA plantations is likely to be in high competition with the international market and the cost of sale of this non-environmentally-based oil may fall as more and more consumers require high-quality organic olive oil. Although a general movement is starting for niche product productions for export or local tourism (*produits de terroir*) – possibly highly adapted to such mountainous regions – future plans should also ensure that local consumption of high quality oil is not jeopardized due to the high price of niche products.

The major ethical question raised is whether it is morally correct to jeopardize agroecosystems that draw on long-standing knowledge that is agro-ecologically robust and important for local food security, in order to develop low-quality olive oil for export to the larger global market? Solutions to face climate risks and food security could draw on farmers' experience and establish a system that integrates high quality niche products, areas dedicated for local consumption and other areas for intensive export-quality oil within a matrix with a high level of landscape and biological diversity.

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# Taming the Black Truffle (*Tuber melanosporum*)

## Safeguarding Mediterranean food and ecological webs

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## Introduction

Mediterranean landscapes are social-ecological systems (SES) shaped by interactions among highly diversified biotas at different ecological scales, coupled with human activities since the Neolithic (Grove and Rackham 2003). They host a large diversity of agrosylvopastoral systems that mimic dryland savannahs, and combinations of interconnected and complementary terraces, pastures and forests.

Mediterranean SES provide food security through simultaneously producing fodder, pasture lands and related animal products, cereals and pulses, and honey as well as a large set of wild edible herbaceous species, saprophytic mushrooms, animal and tree-related products including acorns and nuts, leaves, bark, wood and a large diversity of associated ectomycorrhizal mushrooms such as chanterelles (*Cantharellus* spp), boletes (e.g. *porcini Boletus edulis*) (Zambonelli & Bonito 2012) and truffles (*Tuber* spp).

Among the most esteemed food products in the Mediterranean region are two truffle species, the Périgord Black Truffle (*Tuber melanosporum*) and the Italian white truffle (*Tuber magnatum*). The Black Truffle has now been exported though cultivation outside the Mediterranean realm to Australia and South America. Desert truffles (*Eremiomyces* spp., *Terfezia* spp. and *Tirmania* spp.) are also prized in the Middle East and North Africa (Hall et al. 2007).



## Black Truffle: an iconic product reflecting Mediterranean food webs

The Périgord Black Truffle is generally portrayed as a delicacy of European gastronomy rather than a product linked to food security. Yet, the history of Black Truffle and its dependence on typical vegetation mosaics dominated by young oaks (early stages of forested garrigues) are emblematic of the slow and long transformations of Mediterranean landscapes by human societies. In most places, garrigues are the result of ancient use of fire in a form of swidden-fallow agriculture which has been largely abandoned, and long-term pastoralism that indirectly favored the production of the fruit bodies of *Tuber melanosporum*.

Since the end of the 19$^{th}$ century, the decline of oak-based industries (e.g. charcoal, tannin) and of extensive pastoralism has led to strong landscape shifts, and to a general decline in the area covered by garrigues. This land abandonment induced a dramatic decrease in truffle production (Hall et al. 2007) and the disruption of coupled ecological webs associated with agro-sylvo-pastoral activities and food webs.

The fall of truffle production in the Mediterranean region during the early 20$^{th}$ century has led to intensive efforts by truffle growers, social reorganizations and scientific research to recover truffle production since the 1950s, with results that show patterns of social- ecological resilience (Aumeeruddy-Thomas et al. 2012). These patterns offer insights into how coupled human food and ecological webs may withstand changes.

During the last decade, the development of molecular biology tools propelled an unprecedented production of studies dealing with truffles, and allowed researchers to use modern tools to address ancient questions on the biology and the ecology of the Black Truffle (Le Tacon et al. 2014). On the practical front, the development of technical packages to inoculate host trees (establishing ectomycorrhizal relationships on seedlings in greenhouses) since the 70s enabled the settlement of large areas of planted orchards (Murat et al. 2015) following a classical agricultural paradigm that does not mimic the garrigue ecosystem. In parallel, truffle growers have been trying different techniques based on the memory of past garrigue management, as well as innovations through constant experiments (Aumeeruddy-Thomas et al. 2012).

# The life cycle and ecology of the Black Truffle

The Black Truffle belongs to the Pezizomycetes (Ascomycota). Truffle mycelia develop in soil and colonize tree roots to form ectomycorrhizas with their hosts (oaks, hazel, linden, etc). These plant-fungus chimeric structures are the location of mutualistic interactions: the plant host gains better access to water and soil nutrients captured by soil mycelia, and the fungal symbiont gains carbon produced by the host through photosynthesis. The presence of the truffle mycelium below ground is often reflected above ground by the presence of a *brûlé* extending from the trunk to the limit of the host canopy, and where the development of herbs and shrubs is strongly affected. The mechanisms underlying the formation of *brûlé* are still unclear and may include phytotoxic effect of volatile compounds synthetized by truffle (Streiblová et al. 2012).

The fruitbody (hypogeous and tuberculate ascocarp) of the *Tuber* species, the so-called truffle, is the product of the sexual reproduction of two parents differing by a mating type gene (Rubini et al. 2011b). Millions of meiotic spores are produced in truffles, where one parent – the maternal one – forms the flesh of the fruitbody and feeds it through neighboring mycorrhizas, and the other parent – the paternal one – is only present in spores, and has never been observed as mycelium and/or ectomycorrhiza near the fruitbody (Rubini *et al.* 2011a). At the population level, the spatial aggregation of maternal individuals sharing the same mating type has been repeatedly observed in planted orchards (Rubini et al. 2011a; Murat et al. 2013) and may limit mating between neighbors. In *T. melanosporum* populations, the distribution and the life-style of paternal individuals is still poorly understood, and raises the question of the conditions that favor reproduction, and thus, truffle production.

The Black Truffle's pedo-climatic conditions are quite broad, but favorable soils are generally porous and calcareous with alkaline trends (Jaillard et al. 2014), reduced organic matter content and high biological activities (microfauna; Callot, 1999). As an endemic Mediterranean species, the truffle requires summer drought and high summer temperatures (Bonet et al. 2011). Rainfall distribution patterns drive truffle production (Le Tacon et al. 2014) and ongoing climatic changes may favor the expansion of *T. melanosporum* to higher latitudes (Büntgen et al. 2015). In planted orchards and in spontaneous truffle grounds, irrigation offers valuable supports to truffle growers (Olivera et al. 2014).

*T. melanosporum* is well adapted to highly disturbed ecosystems; this early-successional fungal species establishes during secondary successions in vegetation mosaics where scattered oaks (*Quercus ilex*, *Q. pubescens* and *Q. coccifera*) dominate a matrix of shrubs and herbs. Multiple ectomycorrhizal shrub species transitorily coexist before the arrival of Mediterranean oaks, and progressively decline after complete canopy closure. In this typical habitat, *T. melanosporum* is a member of highly diverse fungal communities (Taschen et al. 2015). In this vegetation, the Black Truffle establishes on oak roots only before canopy closure, and shows poor affinities with co-occurring ectomycorrhizal (ECM) shrubs (*i.e. Arbutus*, *Cistus*, *Helianthemum*; Taschen et al. 2015).

In *brûlés*, some plant species, named 'companion species' by truffle growers, resist the deleterious effect of *T. melanosporum*, while others disappear. When considered altogether, biotic interactions in truffle grounds are diverse, and nested from the direct host-symbiont physical link (ectomycorrhiza), to the indirect and truffle-mediated plant-plant interaction within the *brûlé*, and including interaction among fungal species within the species rich ECM communities. From this perspective, truffle grounds are made of functionally interconnected but spatially disjointed sources of fungal inoculum and sexual partners for established truffle mycelia.



## Social-ecological resilience: the truffle economy, market structure and institutions

The ancient Greeks and the Romans held the Black Truffle in high esteem. In medieval times truffles were used in rural areas as a food resource by farmers and they became a delicacy for rich tables only during the Renaissance. Chatin (1892), who amassed extensive production data from 54 French regions, estimated that 2,000 tons were collected annually in France for national markets and for export. The market structure was based on truffle brokers who collected truffles for sale in renowned truffle markets such as Carpentras in France. The existence of specialized markets is an indication that farmers were probably not merely collecting truffles haphazardly. Production was at its peak at the end of the 19$^{th}$ century and declined progressively reaching an average amount of 20 tons in 1996 (Olivier et al. 2012). This crisis led to a radical re-organization in knowledge exchange networks between truffle growers and between the latter and scientists. The market structure also changed radically. New marketing approaches were based upon direct selling by truffle growers, with a parallel collapse of the "broker" system. The latter favored secrecy and speculations rather than information exchange. During the last decades, a much larger diversity of market places, ranging from large well-known markets to village-level truffle markets, flourished in the form of small fairs. A high quality control was established at the national level and was enforced by the Fédération Française des Trufficulteurs as well as regional federations which developed in the 1970s in response to the truffle production collapse.

# From knowing the "places" to co-constructing with researchers

At the end of the 19th century, farmers knew of "places" that were productive *brûlés*. Secrecy was the only way of "controlling" the places. Historical texts indicate that farmers used a small hoe to slightly till the soil of the *brûlés*, thus provoking small disturbances. Other techniques including that of leaving small pieces of truffle after harvesting aimed at "sowing" the truffle in analogy with the action of planting seeds.

Truffle growers made diverse attempts to propagate truffle trees based on empirical experience. In the 1860s, the *Phylloxera* crisis affected large areas of vineyards. Natural recolonization of agricultural landscapes by holm-oak allowed the production of large quantities of truffles. The observation of this phenomenon led farmers to start planting acorns from tree highly productive in truffles, creating what was known as "Plants planteurs" (Chatin 1892) including attempts to inoculate with small pieces of truffle. In the 1970s, the French Agronomic Research Institute (INRA) developed an inoculation process that led to large plantations in France and elsewhere in the world. However, production hardly increased and reached its peak in 2005 with 40 tons.

The inoculated system recently developed by INRA induced the development of specialized large commercial nurseries. Subsidized inoculated plants became the norm as well as plantations of inoculated trees. In Languedoc, our previous studies show that truffle growers' response to these incentives has been much more complex than simply adopting the agricultural package proposed. Indeed, truffle growers, especially those with old family plantations and truffle woods, recovered elements of this truffle landscape. They maintained the old plantations of their forefathers and natural truffle woods and inserted new plantation trials following the techniques proposed by INRA (Aumeeruddy-Thomas et al. 2012). While agricultural chambers were designed for orchards of even-aged inoculated truffle trees, some truffle growers were experimenting with the creation of these complex mosaics at landscape level. According to their empirical knowledge this mosaic is favorable to truffle production (Aumeeruddy-Thomas op. cit). Sets of practices developed by truffle-growers included techniques that maintain the habitat open (canopy-pruning) and disturbed (soil tillage) as in its typical vegetation.

The necessity to try and recover truffle production led to a reorganization of knowledge systems. The previously secretive system shared vertically (father to son) within family and intimate circles was progressively transformed into knowledge horizontally shared between truffle growers within regions, at national and international favored by the creation of federations of truffle growers at regional and national levels. Furthermore, experimental stations that were established to test and follow truffle productions under the supervision of the Agricultural Chambers favored interactions between truffle growers and technicians. The shift from a vertical to a horizontal system of exchange based on larger exchange networks led to the wide sharing of empirical techniques such as tree pruning, watering and mulching. The most recent technique invented by truffle growers is that of the truffle trap. It is spreading very widely, and many examples are posted and explained thoroughly on the internet. The approach consists generally of excavating the soil in a part of the *brûlé*, filling it with a mix of soil and peat with a few grams of mature truffle. The truffle grower may use a driller to access the roots which are hurt purposefully to force the latter to develop new roots. This truffle trap technique is at the center of much debate, exchanges among growers and new designs, and is the object of attentive research protocols (Richard et al. forthcoming).

Large research projects such as the ANR SYSTRUF or the European MYCOSYLVA have proved that progress and innovation can now be based on an exchange of ideas between local and scientific knowledge.

## Synergies between local and scientific knowledge

A literature review of species which persist on the *brûlé* shows lists of plants that can grow on the *brûlé* naturally, despite the toxic compounds that eliminate most plants (Martegoute & Cordeau 2002). Scientists for their part had identified many plants from several lineages (from monocots such as orchids to eudicots such as *Cistus* spp) that could host Black Truffle mycelium without leading to the production of the fruit body (Gonzales Armada et al. 2010). The results of a large survey among truffle growers in Languedoc shows that truffle growers selectively manage companion plant species on the *brûlé*. Some plants are systematically eradicated while others are protected, if not favored through sowing. These plants are perceived as having an enabling effect on truffle production – as stepping stones for providing suitable fruiting habitat for truffles or through producing disturbances with their roots that may initiate fruiting. Truffle growers manage the plant communities of the *brûlé* and also take into account plants outside the *brûlé* as potential stepping stones for enabling truffle production within the *brûlé*. Indeed, truffle growers provide lists of plants which they consider favorable to truffle production outside the *brûlé* – a vision which integrates the nested ecology of the disjointed tree-host-*brûlé* patterns within the overall ecosystem. Both initial scientific findings and grower's practices helped develop a hypothesis to test the effect of companion species through bringing together local knowledge and scientific knowledge (Photo 1). Experimental set-ups within mesocosms (controlled plantations) with different companion plant species, including some designated by truffle growers, have been attempted and are likely to offer promising insights into the mechanisms involved in these complex interactions primarily detected by the accurate observation and ingenious empiricism of truffle-growers (Taschen et al. forthcoming) (Photo 2).

*Photo 1*
*Assistant researcher working with truffle growers accompanied by their dog, for recording truffle production on a* brûlé *where the latter had placed small signs to follow their growth.*
*© Elisa Taschen, 2014*

*Photo 2*
*Mesocosm experiment with inoculated oak trees with selected companion plants at the experimental station of the Center for Functional and Evolutionary Ecology, Montpellier.*
*© Elisa Taschen, 2015*

# Discussion and conclusion

The crisis in truffle production is linked to the historical transformation of the garrigue ecosystem, largely related to the decline of human-based activities. The ecological niche of the Black Truffle coincided with ancient regimes of anthropogenic disturbances in these ecosystems. The closure of forest canopies and the collapse of pastoralism-mediated disturbances probably governed truffle decline in these Mediterranean landscapes. The current synergy between technical innovation by truffle growers and scientific progress aims at recovering truffle productivity. While scientists have primarily focused their research on the *brûlé*, truffle growers still consider the interstices, the frontier areas, in between two *brûlé* as an integrated part of a larger system, for instance for companion plants. This is a possible area for further research and experimentation.

Technical inventions by truffle growers such as the truffle trap now clearly demonstrate the existence of a large exchange network between truffle growers who constantly discuss their on-going experimentations. This major shift from vertical knowledge transmission (father to son) to a large horizontal system of sharing knowledge – including with researchers – is a major sign of an emerging body of shared knowledge which is a key trait of cultural and technical development. This is a prerequisite for the emergence of a domestication process. The restructuring of the truffle market based on quality and regional origins is also an important situation that drives techniques in source production areas.

However, the domestication paradigm which has prevailed regarding man- plant or man-animal interactions faces a major challenge regarding complex interactions that imply not only mutualistic linkages between two organisms forming a chimeric body, but also interactions with a large set of other ECM fungi and companion plants linked belowground by invisible mycelial networks.

Large-scale plantation of inoculated trees grown in nurseries has not yet succeeded in recovering half of the amounts produced at the dawn of the $19^{th}$ century, although we hope that time will favor these plantations, especially if they are progressively re-configured. It seems, however, that the strictly agronomic approach with even-aged plants may need to reconsider an ecological engineering approach at the landscape level.

The taming or domestication of the truffle, as an element of human Mediterranean food webs, will probably also require the taming of complex truffle ecological webs and biotopes. Such an approach may greatly benefit agricultural approaches in general and is indicative of the absolute necessity today to move from high input agricultural techniques towards agroecological approaches.

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# The argan agroecosystem

## Local meanings of argan tree and bee diversity within man-made territories

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## Introduction

Argan agrosylvopastoral territories in Morocco illustrate the intertwined issues related to climate change and food security in southern Mediterranean semi-arid rural areas. The argan tree (*Argania spinosa* L. Sapotaceae) acts as a shield against desertification and represents the most important southernmost tree formations in Morocco. Its resources have been a pillar of food security in this region at least since medieval times (Ruas et al. 2016). Argan oil is not only a staple food – the tree is a keystone species that supports a large set of food products including domestic animal products (goat: meat, milk), pollinators (honey bees: honey) and other products including almonds, olives, figs cereals, pulses, wild medicinal herbs and animals. The regeneration of the argan tree and transformation of its resources into food products draw on a wide range of empirical knowledge and know-how that should be taken into account if sustainable development goals are to be considered seriously.

The argan tree is endemic to Southwestern Morocco. Its nuts produce an oil that has become a popular cosmetic item over the last decade as a result of national and international development policies and trade (Simenel et al. 2009). Argan forests represent an ecosystem which harbors a rich Mediterranean flora (Alifriqui 2004; M'hirit et al. 1998) but is under threat from desertification, pastoral exploitation and transformation for large scale horticultural productions. Classified as a UNESCO Man and Biosphere Reserve in 1995, the argan area occupies 10% of the national territory and is inhabited by 3.2 million people i.e. 10% of the national population (El Fasskaoui Brahim 2009). Approximately half of this population is rural and is composed of sedentarized berberophone and to a lesser extent arabophone tribes. The argan tree grows in fields (*igran*), horticultural areas (*ourti*), and forests (*tagant*). Forests cumulate pastoral and nut harvesting activities following calendars and rights of access established by customary institutions such as the *agdal*, a system widespread in Morocco (Genin & Simenel 2011, Auclair et al. 2011).

Little attention has been paid by development policies to local knowledge pertaining to trees and forests. Furthermore, development agencies have adopted a marketing approach portraying the oil as "natural" and the tree and forest as "wild". This denies the domestic origin of the product and the important role of humans in the configuration of argan tree populations. The wild collection of argan nuts used by women in oil cooperatives is often emphasized, as well as the folkloric dimensions of its use, whereas integrated arboriculture and pastoral activities requiring specific workloads and social organization are overlooked. This symbolically blurs the role of local social groups which have transformed and domesticated the habitats and the tree over the centuries of human-argan ecosystem mutualism.

## Historical forest construction

The soil and infrastructure of argan forests reveal the footprints of intense ancient human activity. Argan forests contain land infrastructures in the form of ruins, such as the ruins of earthen walls, water retention walls and fencing, but also occasionally the ruins of dwellings and stonework which reflect ancient agricultural and horticultural activities. Whether intact or completely dilapidated, these diverse infrastructures of past farms can be mapped in the forests (Simenel, 2011) and bear toponyms which are markers of the territory. These toponyms and ethnohistorical records show that the forests were horticultural and agricultural spaces in the past, which were subsequently abandoned and returned to their natural state.

Past man-made infrastructure is crucial to understanding argan forest development. For example, dense wooded parks – especially in the uplands – are associated with previous agricultural plots scattered within the forest. Stone removal in rugged land for agriculture resulted in an increase of soil water retention capacities. Shallow terraces reduce the inclination of slopes while the construction of dry stonewalls, earthworks, fencing, or the retention of runoff waters in plots also limit water stress. Finally, walls serve as shade and shelters – humidity sensors that are suitable for argan tree regeneration. Ravine maintenance, stone consolidation in rivulets (*wadi)* beds throughout the plots and small dam constructions all prevent overflow and the erosion of flooded areas. These structures divert water to cultivated terraces through flow channels that circulate along the plots. Although abandoned, this infrastructure still shapes a space conducive to argan tree germination and forest development, as it entails an orderly method for containing rainwater. Past land transformation for agriculture has thus enabled argan forests to take root where they would not have thrived without human endeavour. Water and soil conservation development techniques have changed the landscapes, giving them greater environmental plasticity and enabling the expansion of argan forests and related flora such as the endemic Macronesian flora. We argue that a large part of these argan forests linked to ancient fields and horticultural areas have been favored by human activities and know-how and would not thrive naturally.

Similar situations are found in West African forests, where J. Fairhead and M. Leach (1995) came to the conclusion that "current or previous land use enables the forest to grow in the savannah, even though it would be impossible given the absence of necessary conditions in terms of soil structure, moisture, fire limitation, and types of seeds." Southern Moroccan argan forests represent another important example which highlights the effects of human interactions with the local environment and the development of forests too commonly referred to as "wild".

Argan trees linked to human maintenance have also undergone selection practices which affect tree populations. The fields are a space where we observed on-going argan domestication activities. Practices include maintaining spontaneous sprouts in artificial (walls, benches, ravines) or natural (thalwegs, boulders) microreliefs, protecting and maintaining rootsuckers, seedlings, pruning, thinning (cutting to select a single stem), and selection.

Moreover, animals that graze in the fields after harvest eliminate argan seedlings which are considered the least vigorous, and people recognize that those that are naturally protected – either by spiny plants (e.g. Euphorbia) or as a major stem within coppices protecting each other – are the most vigorous and are therefore simply kept and trained, trimmed and pruned to become a tree. Each argan tree is therefore the expression of the work of several generations of people, from those who protected it from infancy and selected the best strands, to those who have maintained and protected it, and those who sometimes may cut it in order to clear the area for planting other crops or to favor another vigorous tree.

The selection of argan trees according to specific characteristics is based on a kinship terminology between trees. Suckers growing from the roots of original trees are called daughters (*ilis*), while other suckers that grow at the foot of a tree are named uterine nephews (*ayao*) following similar terms applied to human lineages. The morphological criteria used by women for the selection of trees to be kept are the shape of argan tree shells and kernels, the softness and timing of maturation and in some cases exceptionally large trees associated with historical activities (e.g. the Argan souk – the tree under which people used to rest while travelling to the souk). As specialist preparers of argan oil, women define the typology of nuts. According to their classification, there are long and thin kernels as well as small and thick ones (*tarzift*, *tazdit*, *tdnit*), soft (*tekhlouf*), and easy to break as opposed to hard to break (*tamelhkot*). The trees are thus selected individually. Nuts are harvested once a year in July-August after the fruit has matured. Women first harvest the trees with early fruiting and fruit shells that are easy to break, probably those least resistant while those which are hard can remain on the ground before being collected. Hard nuts can be sold at a higher price before the kernel value falls on the market and once the harvest is finished. They also set aside the hard-to-crack nuts, which they soak in water to soften. If crops are harvested tree by tree, the women will not finish until their handmade wicker baskets are filled with a mixture of kernels of different shapes and sizes, a highly valued diversity that is considered necessary to produce the very best taste for a good argan oil (Photo 1).

*Photo 1*
*A woman shows her basket full of different types of argan kernels. Imi n Tlite Region.*
*Y. Thomas, 2008.*

This example of the selection of argan trees by women shows how they interact with the argan tree populations to provide food security through favoring diversity in a context where climate risks are high. Their oil production strategies linked to long-term intergenerational selection processes play a major role in the management and regeneration of the genetic diversity of the argan tree population.



## Beekeeping: intimate linkages to the mosaic of argan territories

In Southwest Morocco, beekeeping is closely associated with the mutualist interactions between Berber and Arab groups and this unique agro-forestry system centered on the argan tree over the millennia. The know-how of beekeepers is based on the manipulation of differential agrosylvopastoral spaces. Indeed, although beekeeping in southern Morocco can be qualified as sedentary, bee hives may alternately leave spontaneously and/or be placed in cliffs associated with waterfalls, cereal fields co-existing with argan trees, horticultural spaces, monoculture of prickly pears (*Opuntia indica*), or pastoral areas dominated by *Euphorbia spp*. and argan trees. Each spatial unit of this rural territory supports a different degree of the domestication of yellow Saharan domestic bees, from wild swarms living in autonomy in the cliffs to the most domesticated hives found near houses or in sophisticated collective hives (Photo 2) (Simenel et al. 2015).

*Photo 2*
*A beekeper and his traditional hives, Mesti Region.*
*R. Simenel, 2016*

According to the season and the beekeeper's needs, the latter decides to place his hives in a different space within the landscape mosaic, to favor the collection of new colonies or honey production and/or their health, their rapid division, or their protection in the event of extended drought. Colonies of domestic bees – mostly the endemic Saharan yellow bee – play an essential role in pollinating the argan trees. The mobility of the hives in this agroforestry mosaic is not negligible. Maintaining hives close to homes within prickly pear, or installing them in an arboreal closed area bordering fields encourages bees to pollinate argan trees located in the agricultural zone. From these locations, the bees cover a distance from homes to argan forests, extending over the whole of the cultivated area. The need for pollination is important in the fields where the density of argan trees is high and where some trees may bear fruit twice a year in contrast to argan in forest areas. According to beekeepers, the pollination of argan by bees allows the production of fruit to be doubled. Argan nuts from fields make the most of harvested nuts. Pollination of argan forests is ensured by domestic swarms located in the cereal-argan cultivated areas during droughts, as well as wild bees housed in the cliffs and other pollinating insects or mammals.

Bees do not collect only nectar and pollen from these differentiated spaces; they also collect a significant range of beekeeping materials essential to the good health and reproduction of the swarm. Beekeepers identify all aspects of the bee life cycle, taking into account their uses of plant materials collected. They then evaluate their effects on the development of the hive and the behavior of the bees. The availability of this plant diversity stems from a remarkable spatio-temporal concordance between human practices and bee activities.

According to the knowledge of beekeepers, some plants play an essential role in the development of the various constituent stages of beekeeping, from the evolution of the brood to the swarming (Simenel et al. 2015). The most important plants are those used by the bees to eradicate the Varroa. Varroa is one of the suspected causes of Colony Collapse Disorder. Berber-speaking beekeepers claim that their bees are able to reduce the impact of the disease by using certain plants that are important sources of propolis. In this category are found substances such as the latex of *Euphorbia echinus*, *Euphorbia balsamicus* or the *Ononis sp.* exudate, in addition to the juice of *Senecio anteuphorbium*. According to beekeepers, the degree to which the latex harvested by bees is "peppery" (*harr* in the local language) determines their effectiveness against the Varroa mites. The ethnoecologiocal knowledge of beekeepers may thus contribute to combating Varroa by moving the hives to places where the desired plants are present in higher density.

Across the generations, men and women have shaped an ecosystem and respected the requirements of the nutrition and health of bees through facilitating their access to specific nectar resources and their interactions with plant substances distributed in different spaces with distinct ecologies and following temporal variations relating to the hive development stage and a large diversity of plant flowering phenology within the territory. Bees have thus been fully integrated into the rural landscape by the beekeepers. The mutualistic relationship between bees and men enables both the pollinating of argan trees and the nurturing of bee colonies. Bees and men here can be considered as the co-constructors of this agrosylvopastoral system and its associated biodiversity.

For ten years, the mutualistic and strongly territorialized relationship between southwestern Moroccan beekeepers and Saharan yellow bees has faced the intrusion of modern beekeeping practices. These industrial practices, whose sole purpose is the production of honey, are based on a standard model of modern hive, carrying with it swarms of black bees from northern Morocco. Today, research fails to measure the impact of such an intrusion on the settlement of the Saharan yellow bees and therefore on the agro-ecosystem pollination process, but preliminary field observations suggest the presence of hybridism and displacement of distribution of the yellow bee further south. Similar to what is proposed by Oldroyd for the American case, one of the likely risks causing the disappearance of bee populations certainly lies in changing cultural practices – and especially in this case, the abandonment of a territorial vision of beekeeping.



# Conclusion

Argan territories constitute a mosaic of agro-sylvo-api-pastoral areas whose construction is inextricably linked to practices and know-how such as beekeeping and arboriculture. With the young generation disregarding peasant activities such as the maintenance of terraces, pruning sprouts, and fertilizing fields, there is a risk of the gradual deconstruction of this mosaic. This would lead to the end of the contribution of the rural population to the regeneration process of the argan tree based on multigenerational practices. The loss of knowledge relating to the argan tree is further threatened by marketing activities surrounding the production of argan oil as a cosmetic product which denies the role of local knowledge (Simenel et al. 2009).

The argan forest maintained by humans could possibly decrease in coverage due to lack of care by humans. Subsequently the role of this man-made forest as a shield against desertification may also be weakened. The autonomy in high-quality oil products of local populations also becomes vulnerable in a context where export prices and market structures are within the control of external actors. Climate change may certainly affect the argan territory and its people but social changes here are clearly linked to the resilience of the system. Experts and engineers are increasingly producing new ideas as to how to tame the argan tree, for instance through favoring a few clones that would give a high yield in oil, here also giving little consideration to a millenary system based on nut diversity that has favored both sexual and clonal reproduction. Moreover, the decline of the Saharan yellow bee and related pollination problems including the reproduction of food resources may be affected not only by climate but more importantly by invasion by modern semi-industrialized apicultural practices.



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Sub-chapter 3.3.4

# Pollination: threats and opportunities in European beekeeping

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## Introduction

Pollination is crucial for both crop production and the conservation of wild flowering plants. The honeybee (*Apis mellifera*) is a ubiquitous pollinator and is the dominant pollinator to more than half animal-pollinated crops (Klein et al. 2007), even though wild pollinators are essential to provide optimal pollination services in many crops, not to mention natural vegetation (Garibaldi et al. 2013). However, there is a global decline of insect pollinators across Europe (Potts et al. 2010; Breeze et al. 2014) and the USA (NRC 2007) and a worldwide decline of honeybees, known as Colony Collapse Disorder (CDD) (Oldroyd 2007). In this paper we outline some key elements of this worrying situation and offer some avenues for hope if beekeeping is to be maintained.

# Honeybees as fundamental elements of services of pollination and food production



Out of the fifteen ecosystem services identified by the Millenium Ecosystem Assesment (2005), pollination is described as one of the most important (Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services, IPBES 2016). Animal (mainly insect) pollination is crucial for many cultivated crops, and is known to significantly increase the productivity of 85% of 264 crops cultivated in Europe (Williams, 1994) and for about 70% of 87 main crops cultivated worldwide (Klein et al. 2007). Over the last five decades, global agriculture has become increasingly pollinator-dependent, with an increase by a factor of 3 in the number of crops requiring the intervention of pollinators (Aizen & Harder 2009). Spatial analyses demonstrate that approximately 10% of the worldwide agricultural surface is pollinator dependent (Gallai et al. 2009), but this dependency is far from uniform across the globe (Lautenbach et al. 2012) and may reach as much as 30% in several agricultural hotspots. The global value of insect pollination, in which honeybees play a prominent role, has been estimated at around 150 billion euros (Gallai et al. 2009). Moreover, agricultural and biofuel policies from the European Union have encouraged the substantial growth of insect-pollinated crops throughout Europe.

Beekeeping is linked to the production of honey and, to a lesser degree, wax, propolis, royal jelly, pollen and venom. While bee products are used mainly as foods, which are recognized as incredibly high sources of micro-nutrients (vitamins, iron, mineral elements, etc.) their contribution to human health – especially in developing countries – should not be overlooked (Chaplin-Kramer et al. 2014): they intervene in countless therapeutic practices and traditional healing systems, and are therefore of paramount value for the wellbeing of the citizens in low- and medium-income countries (Chaplin-Kramer et al. 2014; IPBES (chap. 5 2016). However, at the same time, the global decline of wild pollinators is now evident (Goulson et al. 2008) and parallel declines of insect-pollinated plants have been observed locally (Biesmeijer et al. 2006).

Similarly, a decline in managed honeybees and beekeepers has also been demonstrated in recent decades in Europe (Potts et al. 2010) and in the USA (NRC 2007). Breeze et al. (2014) demonstrate that the recommended number of honeybees required to provide crop pollination across 41 European countries has risen 4.9 times faster than honeybee stocks between 2005 and 2010. In 22 out of the 41 countries studied, 90% of the demand for honeybee stocks is not met. Unsustainable practices have been regularly denounced, as in the USA, which has developed the largest pollination exploitation industry: more than two million honeybee colonies are proposed for rent in order to pollinate vast monocrop fields and plantations (Morse & Calderone 2000).

The use of honeybees as a unique pollinator species is a particularly risky strategy, given that at least half of the rented hives have to be transported over long distances across the country to California to ensure the pollination of almond (*Prunus dulcis*) orchards for a period of six weeks (Sumner & Boriss 2006). An irreversible situation of 'no pollination's land' is already reached in a growing number of Asian countries, where local plantation workers are obliged to pollinate the trees, for instance apple trees, by hand, replacing the absent natural pollinators; a situation caused both by a drop of native wild pollinators and the unavailability of honeybees for this pollination service (Partap & Partap 2007).

Taken altogether, these studies alert us to the significant threat of the enhanced vulnerability of worldwide food production induced by the decline of (wild and managed) insect pollinators (IPBES 2016). The resilience of this food production system relies heavily on the capacity of many countries to cope with major losses of wild pollinators. Such a dramatic situation also highlights the numerous critical gaps in our current understanding of pollination service supply and demand, and highlights the pressing need to invest in further research into this issue (Breeze et al. 2014). If we are to make actionable policy out of these general concerns, we must identify the areas that are most vulnerable to the ongoing decline in pollination services and investigate the many ramifications resulting in a deterioration of human wellbeing (Chaplin-Kramer et al. 2014; IPBES 2016). Cooperation between sustainable agriculture and beekeeping as well as a clearer understanding of pollination service supplies and demands on different scales offer some pathways toward a more resilient pollination-dependent crop system.

## Towards the homogenization of beekeeping practices and use of several honeybee landraces

Up to the beginning of the 20th century, beekeeping was essentially guided by traditional practices along with the use of local honeybee landraces. These landraces were adapted to the constraints of the local environment and had generally lasted for several centuries.

Through constant observation of bee activities and behaviors, traditional beekeepers have developed empirical and sophisticated knowledge about their bees and the related bee products (Dounias & Michon 2013). They have gained extensive understanding of local climate variability and fluctuations as part of their traditional ecological knowledge that are acquired and transmitted through generations (Berkes et al. 2000).

However, most of the local knowledge sustaining local beekeeping practices have been drastically weakened by global change together with the bee strains with which they had evolved. Since World War II, human activities have increasingly impaired the planet's ecosystems, but at different amplitudes depending on the regions, and with a noticeable contrast between developing and developed countries (IPBES 2016). Consequently, beekeeping is characterized by a wide range of practices, from the gathering of wild honey in natural colonies to the industrial exploitation of domesticated honeybees. In between these two extremes, a vivid continuum of domestication provides a broad variety of traditional forms of beekeeping that are grounded in the specificities of local socio-ecological features (Crane, 1999). In Europe, the modernization of agriculture over the past century has induced profound changes in land-use systems and landscape fragmentation but also an exponential increase in the use of pesticides and insecticides. Beekeeping has also been deeply transformed, notably via the spread of movable frame hives, which enable the beekeepers to harvest honey without destructively cutting out the wax combs (Crane, 1999). However, because the beekeeping of the single domesticated honeybee initially appears homogenous throughout Europe, understanding of how this activity has evolved at a very local level is generally overlooked (Lehébel-Péron et al. 2016). Such an understanding is nonetheless crucial if appropriate community-based resource management is to be developed in socio-ecological systems that have been profoundly shaped by beekeeping activities.

*Photo 1*
*Log hives used in traditional beekeeping in the Cevennes region.*
*© A. Lehébel-Péron*

To illustrate this necessity, a recent study was carried out focusing on the ethnoecological history of local knowledge regarding beekeeping in the Cévennes National Park (southern France). The goal was to trace back the major episodes of local beekeeping, by considering the modifications of chosen beehive models and bee landraces, as well as the valorization of beehive products in tune with evolving social and economic circumstances (Lehébel-Péron et al. 2016). This study revealed a number of salient features, such as the first evidence of the use of log hives in the early 17th century – they were time-stamped and retrospectively set into context. Artisanal beekeeping of the local black bee hosted in log hives persisted until the 1970s, which saw a transition to modern beekeeping using frame hives, selected bee landraces, and the professionalization of the local honey trade sector. Beekeepers from the Cévennes region only later progressed from a domestic and landscaped beekeeping – which was optimized for the context of self-sufficient and multi-activity lifestyle – into windfall beekeeping driven by the search for maximized honey yields and supported by a diversification and a hybridization of bee landraces.

Such combined historical and biocultural perspectives of beekeeping in Cévennes should serve to suggest reasonable outcomes for conservation and help reconcile the preservation of a patrimonial and traditional beekeeping with the enhancement of a still emerging local honeybee market. This example demonstrates that the shift in beekeeping processes has somehow reinforced the resilience of a traditional Cévennes way of living, even if the risk of a loss in local knowledge remains acute.

In Corsica, almost all of the traditional beehives have been destroyed and the local knowledge of traditional beekeeping has virtually disappeared. This extinction is the consequence of the Protected Designation of Origin (PDO) linked to the use of modern hives and the development of a new and labeled honey production. The norms established at the European Union take insufficient account of local knowledge and know-how.

In addition, these major and fairly recent changes in beekeeping practices were also marked by the use of novel landraces of honeybees. The introduction of non-native landraces as well as the displacement of hives (transhumance) to flowering sites that are normally exploited by local and rustic landraces has become customary in the attempt to optimize honey production and cope with the colony losses after the critical winter period (Breeze et al. 2014; IPBES 2016). In several countries of the Mediterranean area, beekeepers currently use several landraces of honeybees. Exotic sub-species, such as the Italian (*A. m. ligustica*) and the Caucasian (*A. m. carnica*) bees or even hybrid landraces like the Buckfast, are chosen according to their reduced aggressiveness and their higher honey productivity (Ruttner, 1988; Crane, 1999; Wallberg et al. 2014). This is what happened in Cévennes, but not in Corsica, where the island factor fostered the persistence of the local honeybee. Favored by the yearly renewal of queens, the spontaneous hybridization of landraces among the hives constitutes an acute problem of modern beekeeping in most Mediterranean and European countries. Genomic analyses indicate that managed honeybees are suffering from a reduction in genetic diversity, not only in Europe with its several native landraces (Wallberg et al. 2014), but also in North America where domesticated bees have been introduced (Harpur et al. 2012).

# The changing world of honeybees, beekeeping and beekeepers

As described above, the paradoxical trends observed at the globe scale between the marked depletion of pollinators and their increasing solicitation for pollination services has led to an unsustainable – if not irreversible – situation. The urgent need to respond to this dramatic threat has only recently been expressed (Breeze et al. 2014; IPBES 2016). Nevertheless, worldwide honey production is dominated by a professional beekeeping sector that must be responsive to the dictates of the market and that is apparently puzzled by global change.

However, wild honey harvesters and traditional beekeepers – mainly composed of local communities and amateur honey producers – could play a prominent role in monitoring the incidence of global change on local biodiversity, through their daily and thorough observations of bees, especially in places where this incidence is insufficiently assessed by the scientific community (Dounias 2009). This local ecological knowledge would help leverage the resilience of communities forced to adjust their livelihoods to the multiple stressors of global environmental change (Gómez-Baggethun et al. 2013; Roué et al. 2015).

Traditional ecological knowledge and local perceptions are being increasingly solicited to reduce knowledge gaps for conservation and mobilized to achieve more effective ecosystem-based management (Berkes et al. 2000). Another study, also in the Cévennes National Park (southern France) exploring the production of heather honey, explored whether combining scientific and traditional knowledge is a promising means to elaborate alternative ways of adapting to ongoing changes that are compatible with local values and priorities (Lehébel-Péron et al. 2015).

The production of this very particular type of honey, which was formerly massively exported to Germany, has dramatically dropped over the last two decades. The study showed that the local drivers of this decline are the result of a combination of factors from the environmental (climate change, landscape closure, pollution, sanitary problems with bees, notably varroa parasitism) to the economic (emergence of competitive markets) and the social (change in practice of agricultural practices). The study also pointed out that the scientific state of knowledge is highly congruent with the perceptions expressed by local beekeepers and the few experts of the heather honey sector. Taken together, the views jointly expressed by the three categories of knowledge and expertise significantly enhance the accuracy of our understanding of the drivers of change affecting heather honey production, much more than when they are taken separately. Once again, local socioecological resilience could be enhanced by the development of a local market that would gain from branding a new 'Made in Cévennes' honey production. This could be a promising way to promote an artisanal yet cost-effective activity that would benefit from the specific biocultural features of the National Park and successfully meet both conservational and development goals.

# Perspectives for pollination by honeybees and beekeeping

Given the urgent need to tackle the incommensurable threat of the pollination paradox, solutions are surely to be found in a complex transition toward a truly sustainable agriculture and meaningful cooperation between agriculture and beekeeping, but also in a better match between supply and demand. However, the large variety of beekeeping practices and the diversity of ecological and socioeconomic situations between developing and developed countries necessitate the adoption of joint strategies at the very local level. If professional beekeepers were to develop more sustainable practices, local beekeepers and honey gatherers would have to adjust their adaptive responses to change in ways that do not impair the integrity of their livelihoods.

Supporting the varied local production of native honeybees while encouraging more eco-aware practices, along with advocating for the labeling of knowledge-based singular productions while reinforcing the dialogue between experts of different types of knowledge and know-how: these are certainly the key challenges to address in the near future. But acknowledging the expertise of traditional beekeepers and honey hunters is an absolute prerequisite in order to obtain their prior informed consent and ensure their voluntary adherence to any community-based management initiative.



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Chapter 4

# Risk prevention

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## Abstract

The magnitude and occurrence of hydro-meteorological extremes around the Mediterranean are likely to be significantly affected by climate change, which also implies a number of related risks for our societies. Although projections of future trends remain uncertain, our societies must be prepared for these possible changes. This chapter discusses various adaptation measures to natural hazards and risks.

Significantly, the measures being considered are "non-structural": i.e. not based on civil engineering works such as dams, reservoirs or embankments. This corresponds to changes in risk prevention policies in the countries around the Mediterranean. Costly structural measures, designed to control or reduce natural hazards, have shown limited efficacy in the face of extreme events and equally limited resilience to climate change. Structural measures are no longer considered as the only or even the primary possible response to risks, but are being coupled with adaptation measures based on land-use planning and regulations or designed to increase response and crisis management capacities.

The first section of this chapter demonstrates how exposure to natural hazards has dramatically increased in most of the countries around the Mediterranean over the last century, due to significant population growth and the concentration of the inhabitants in urban areas. Socio-economic and demographic changes in the Mediterranean basin have proved far more influential in shaping the consequences of natural hazards than climate change over the last 50 years, and this will remain valid for the near future. Land use planning and regulations accounting for natural hazards are a matter of priority in order to limit the risks.

The next articles in this chapter present an overview of recent progress and future perspectives for weather and flood observation and forecasting methods. Better quality monitoring and forecasting, along with improved organization of population information and rescue services, also provide efficient adaptation measures. They will not help us escape unavoidable catastrophic events but may significantly limit their consequences.



## Résumé

L'intensité et la fréquence des événements hydro-météorologiques extrêmes sont susceptibles d'évoluer notablement en région méditerranéenne du fait du changement climatique. Les projections climatiques concernant ces extrêmes restent certes incertaines, mais nos sociétés doivent se préparer à ces évolutions probables. Ce chapitre évoque des mesures d'adaptation aux risques naturels hydro-climatiques. Il est intéressant de noter que les mesures d'adaptation considérées sont des mesures « non structurelles » : i.e. elles ne sont pas fondées sur la construction d'ouvrages de génie civil, tels que les barrages et les digues. Cela correspond à l'évolution des politiques de prévention des risques naturels dans les pays bordant la Méditerranée. Les ouvrages de protection coûteux, dont le but est de contrôler ou de réduire le niveau de l'aléa naturel, ont une efficacité souvent limitée dans le cas d'événements exceptionnels et une faible résilience aux évolutions climatiques. La construction d'ouvrages de protection n'apparaît plus comme la principale, voire l'unique, réponse possible pour limiter les risques. Les politiques de prévention mettent désormais en avant des mesures d'adaptation fondées sur la maîtrise de l'occupation des sols et l'amélioration des capacités de gestion des crises et des catastrophes.

Le premier article de ce chapitre rappelle que le niveau d'exposition aux aléas naturels a considérablement augmenté en région méditerranéenne au cours du siècle dernier, du fait de la très forte croissance démographique et de la concentration des populations dans les villes. Au cours des cinquante dernières années, les évolutions socio-économiques et démographiques en Méditerranée ont bien plus fortement pesé sur l'augmentation des dommages liés aux risques naturels que les changements climatiques. Cela restera vrai dans un proche

avenir. La maîtrise de l'occupation des sols et de l'urbanisation est donc un élément essentiel des politiques de prévention des risques. Le reste du chapitre présente les progrès récents et les perspectives d'évolution des dispositifs d'observation et de prévision météorologiques et hydrologiques. L'amélioration des prévisions des sécheresses, des pluies et des crues, combinée à une meilleure organisation de l'information des populations et des services de secours, constitue un autre type de mesures d'adaptation et de prévention des risques. Ces mesures n'évitent pas la survenue de l'inévitable catastrophe, mais permettent d'en limiter notablement les conséquences.

# Urbanization and land use as a driver of flood risk

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## Introduction

Obviously, floods have natural causes – heavy rainfall in the case of flash floods – nevertheless, their consequences depend strongly on urbanization and land use. On both sides of the Mediterranean, regions have been subjected to fast changes which have led to a concentration of assets in valleys and coastal areas (Plan Bleu, 2008). Changes in land use play a predominant part in the "risk production process" i.e. in the increasing exposure of human activities to flood risk.

This chapter gives an overview of these land changes and their impact on flood risk, based on documented cases in the Mediterranean.

# Recent catastrophic floods: land use in question

Among the growing damage linked to floods, urbanization and more generally un-adapted land use is often called into question. Three examples taken from three Mediterranean countries (Tunisia, Morocco, Algeria) illustrate the impact of land use with its considerable human and material toll.

## The evolution of the global disasters toll

Such changes can be seen in the evolution and variability of natural disaster annual assessments (fig. 1). Since 1970, the cost of natural disasters has quadrupled, essentially due to an increase in the number and value of exposed assets. Since the mid-1990s, costs have been subjected to high inter-annual variability that does not only concern floods. The years with a heavy toll are those where highly urbanized areas were hit (e. g. Katrina in 2005). The high variability of damage is therefore more indicative of the spatial concentration of activities and population than of increasing natural variability.

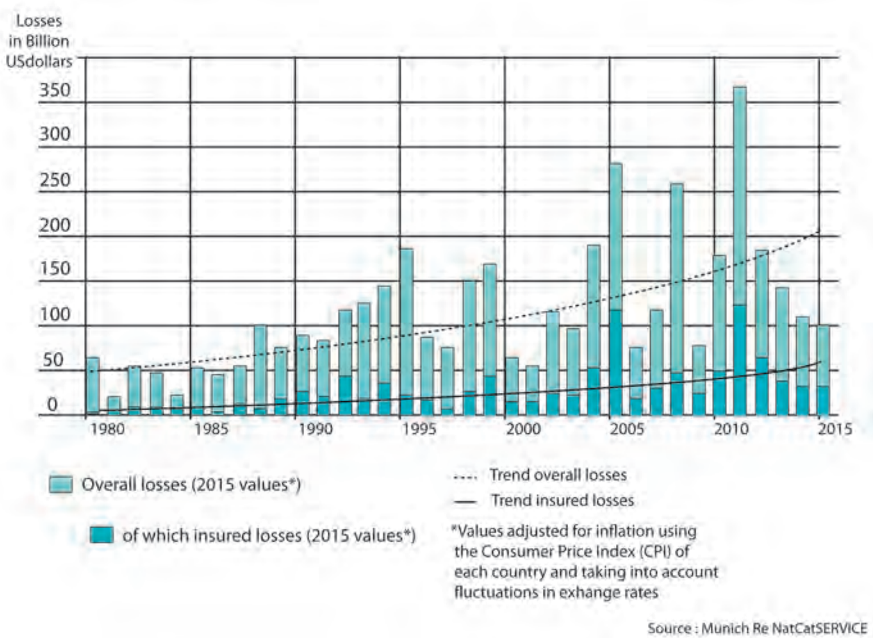


*Figure 1*
*Evolution of insured and non-insured losses for "natural" disasters.*
*Source: MunichRe.*

## Recent floods in the Mediterranean showing the impact of urbanization

Tunisia regularly suffers from torrential floods with considerable human losses (fig. 2). On 13 October 2007, heavy rainfall hit Greater Tunis (70 to 180 mm in 24 hours). 16 people died (Fehri et al. 2009), mostly on the GP8 road to the north of Tunis. Through careless construction, increasing numbers of obstacles (buildings, roads) had been built on riverbeds. Hydraulic works were often under-sized and badly maintained.

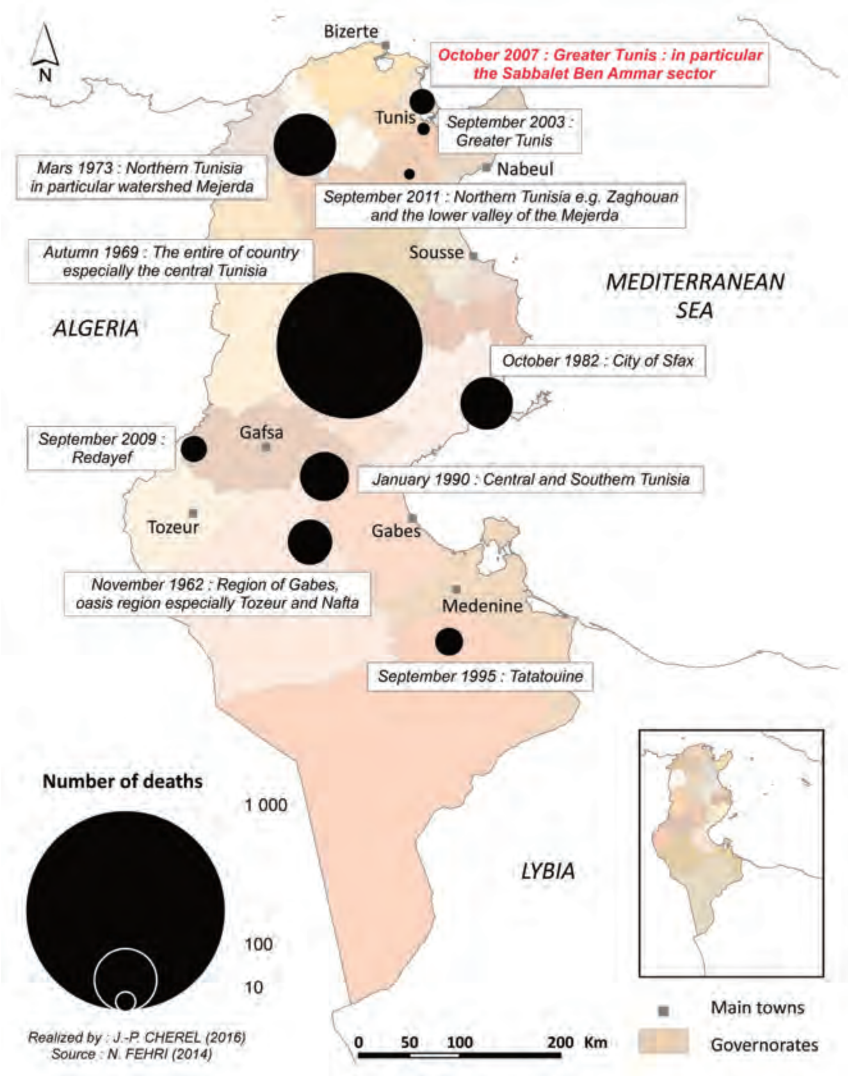


*Figure 2*
*Human toll of main flood events in Tunisia (1962-2011).*

Like Tunisia, Morocco has suffered from numerous lethal floods since the mid-20th century (fig. 3). The one that hit the Ourika valley (503 km², High Atlas of Marrakech) was the deadliest in the country's modern history.

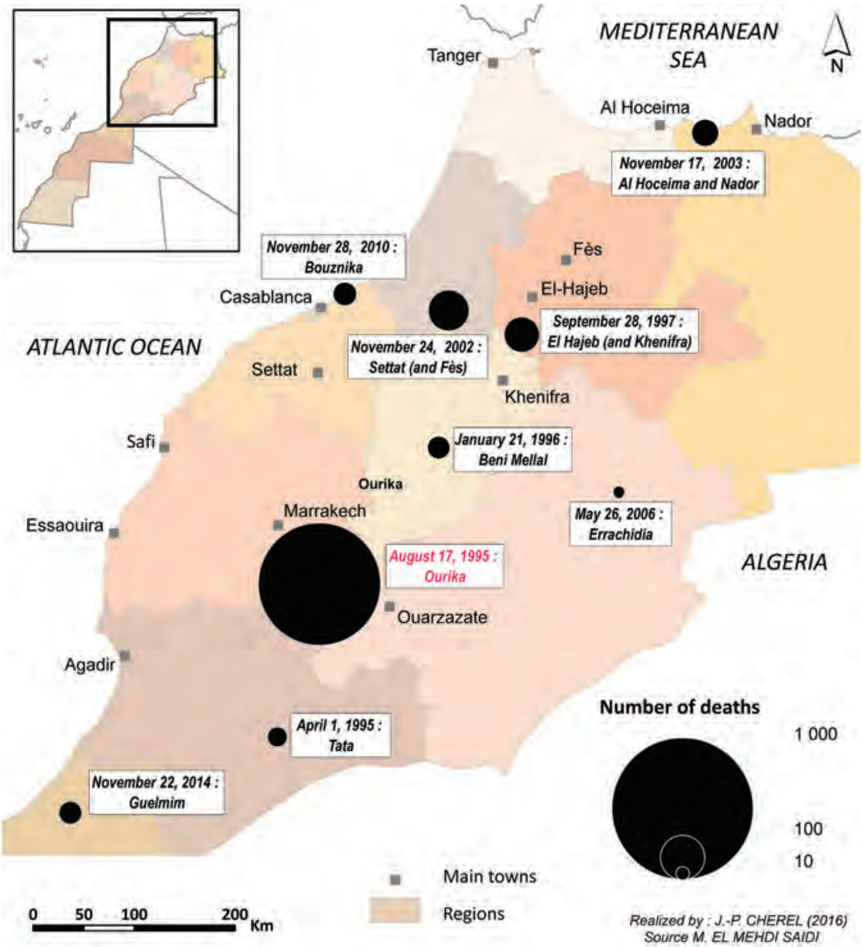


*Figure 3*
*Main deadly floods in Morocco since 1990.*

In the afternoon of 17 August 1995, intense rainfall hit the upstream basin of Ourika to the south of Marrakesh. The peak discharge reached around 1,000 $m^3/s$ in the gorges. This was where the damage was the most severe. The estimated human toll ranged from 289 to 730 people (according to sources) among the 35,000 holidaymakers in the valley that day (Secrétariat d'Etat auprès du Ministère de l'Energie, des Mines, de l'Eau et de l'Environnement, 2008). This toll can be explained by the exposure of both the population and holidaymakers on the river bed. Restaurant terraces were set into the wadi's minor bed. Furthermore, the overcrowding of the valley late in the summer afternoon, combined with the narrowness of the only road, blocked several cars with their occupants. Trapped in their vehicles, the latter did not survive.

The most emblematic case of torrential floods in an urbanized zone remains that of Bab-el-Oued. The huge rainfall of 9-10 November 2001 (263 mm in two days, and above all 70mm in two sequences of 30 min.) triggered both human (781 deaths and 115 missing) and material (3,721 destroyed or damaged houses) losses which had never been observed here before. The most important damage occurred at Bab-el-Oued, situated in the western part of greater Algiers. In two decades (1985-2005) the basin of Wadi Koriche experienced considerable urbanization - up to 78% of its surface was built upon. The basin presents a high predisposition to runoffs in case of intense rain. The inner-basin networks (25 km of roads, 7.8 km of pipe works) served as collectors and enabled the propagation of flows towards the Bab-el-Oued area. The main river bed had been piped and the Chevalet-Triolet highway was built on top of it. Setting up a road network instead of a hydrographic one removed it from the landscape. Gradually, people forgot about it and tended to use the wadi's bed. Most of the victims were car-drivers trapped by the flood on the highway, and people at the Bab-el-Oued market.

These emblematic events show the part played by urbanization in the increased cost of flash floods. The catastrophic tolls invariably result from inconsiderate occupation of riverbeds by economic activities, housing or roads.

## Land use transformations, a key factor in flood related damage

Since the early 20$^{th}$ century, world population growth has been intense. In 100 years (1915-2015), the world's population rose from 1.9 to 7.4 billion people. It doubled between 1970 (3.7 billion) and 2015 (7.4). It ranged from an "empty" Earth to a "fully populated world" – "full" in the sense that we have reached the limits of the Earth's system capacities. This increase in the population was accompanied by deep land transformations which determine the extent of flood-related damage.

### Demographic growth and urbanization

Countries on the north and south sides of the Mediterranean basin have experienced high demographic growth (fig. 4). For example, Morocco's population increased from around 26 million inhabitants in 1994 to nearly 33.8 million in 2014, i.e. over 7 million more people within 20 years. This demographic growth came with spatial redistribution. The population is concentrated in the cities of coastal areas and valleys. The urbanization rate went from 48.6% of the population in 1990 to 60.3% in 2014 (Haut-Commissariat au Plan, 2015).

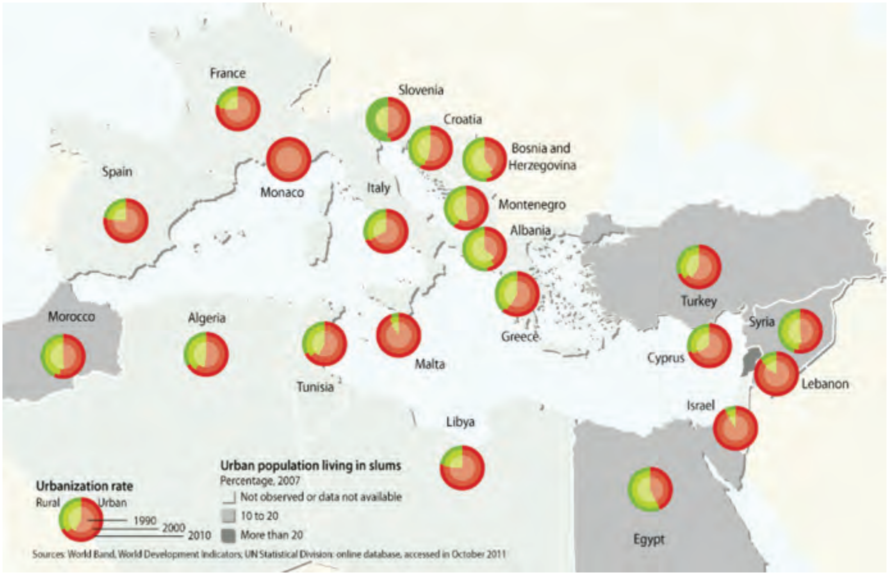


*Figure 4*
*Urban population in Mediterranean countries.*
*Source: Plan Bleu, 2008.*

Most major cities in North Africa experienced demographic growth boosted by rural-urban migration during the first decades of independence. The Greater Tunis population rose from 194,000 inhabitants in 1921 to 561,000 in 1956 and 2.4 million currently. Simultaneously, urbanized areas expanded from 3,387 in 1957 to 28,000 ha in 2012 (source: l'Agence d'Urbanisme du Grand Tunis (AUGT).

In the south of France, the population increased in the plains and regressed considerably on higher lands (Cevennes, Pyrenees).

At the end of the 19$^{th}$ century, the population of the Languedoc (fig. 5a) was balanced between populated countryside and a network of midsize cities. At the end of the 20$^{th}$ century (fig. 5b), the population was concentrated on the coast, big cities and communication axes.

The attractiveness of coastal areas is naturally explained by touristic and industrial activities. In Morocco, 70% of the country's tourism is concentrated on the Atlantic and Mediterranean coasts. The coast is also home to most industrial activities. This trend should continue, particularly with the development of the "Tanger Med" harbor (the biggest in the Mediterranean basin) and the extension of the "Nador West Med" port. However, the concentration in low areas cannot be narrowed down to the appeal of maritime activities. Indeed, many so called "coastal" cities have no major activity linked to the sea (e.g. Montpellier in southern France). The attractiveness of low lands is mainly explained by the proximity to roads.

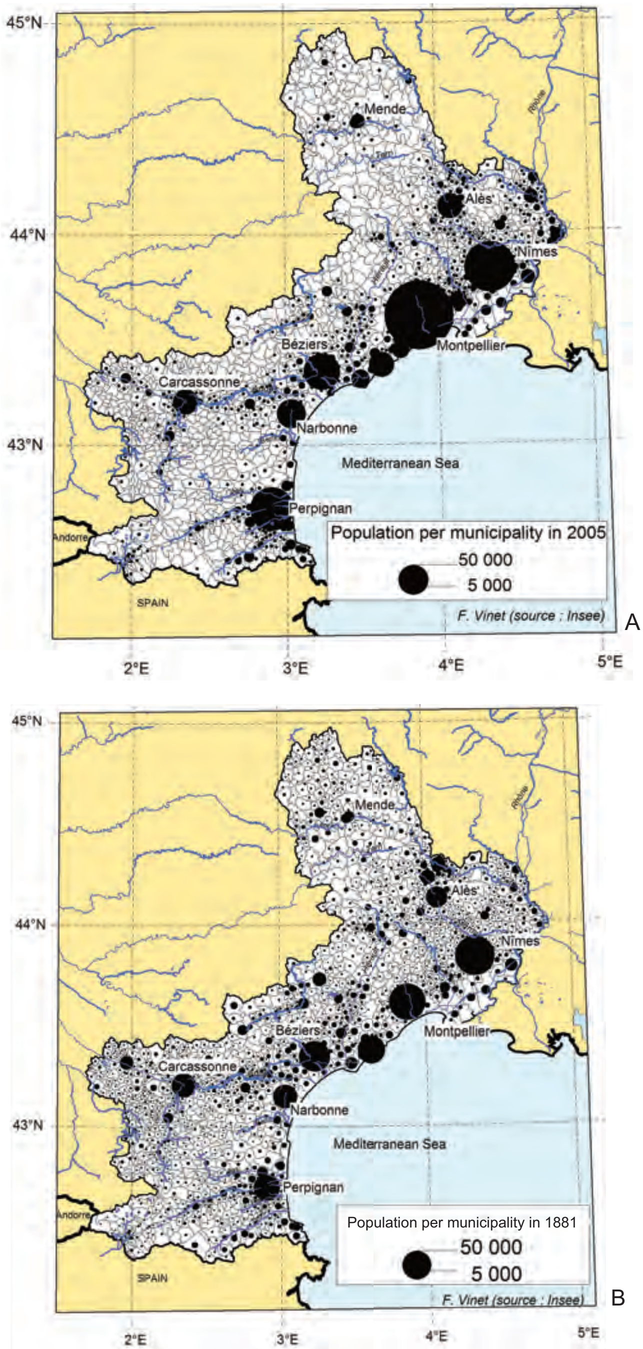


*Figure 5*
*Spatial distribution of population in Languedoc (southern France) in 1881 (fig. 5a) and 2005 (fig. 5b).*

## Population growth and flood risk stakes

Demographic growth and urbanization brought about land and society transformations that induced changes in the assessment of flood risk. As the exposed assets increase and move, social vulnerability and resilience evolve.

The first consequence of these land transformations is the increase in assets in flood-prone areas. As in North Africa, the French population has increased in the last 50 years. It rose from 46 to 66 million inhabitants between 1962 and 2016. As a consequence, real estate increased by 8 million dwellings. Housing demand was met according to urban planning regulations where environmental risk questions remained marginal until the 1980s. Urbanization decisions were based on the available land, in relation to transport networks and activities, without really taking flood risk into account, except some local cases where risk awareness was high.

The assessments of numbers of housing or people living in flood-prone areas must be taken with caution as they vary considerably according to the chosen context. In France the number of people living in flood-prone zones comprises between 6 million and 17 million according to the Evaluation Préliminaire du Risque Inondation body (EPRI) following the setup of the 2007 European directive. French Mediterranean departments are among the most exposed (see ONRN website www.onrn.fr ). The Alpes-Maritimes (+9,200 dwellings in flood-prone zones in between 1999 and 2008), the Var (+8,300 dwellings) and the Vaucluse (+5,800 dwellings) are among the six departments most affected by real estate demand in France.

In Morocco, although the population is concentrated on the coast, the inner valleys have experienced important growth of urban perimeters as in the Souss valley, where newly built zones continue to encroach on the wadi bed, and as in the Jorf and Tarrast neighborhoods in the south of Agadir (Rehaimi, 2013; Saidi et al, 2013). Such encroachments expose numerous populations who are sometimes already vulnerable due to their socioeconomic precariousness.

## Changes in runoff conditions

Besides the increase in exposed assets in risk-prone areas, urbanization results in changes in local runoff conditions. Such modifications are now well known (e.g. Zevenbergen et al. 2010). Apart from the increase in impervious areas, basin urbanization is characterized by changes in runoff conditions by longitudinal and transversal obstacles. In addition, the disappearance of rivers in the urban landscape contributes to forgetting the risk and encourages the occupation of minor and major river beds. The watershed of the El-Ghrich El-Greb wadis north of Tunis is a good example of the impact of expansion and densification of urban areas on runoff coefficients (Fehri and Zahar, 2016). From the 1950s onwards, this watershed experienced rapid urban expansion. So much so that buildings and roads now take up over 70% of its total surface. The exposure of the road network is also a growing danger factor (fig. 6).

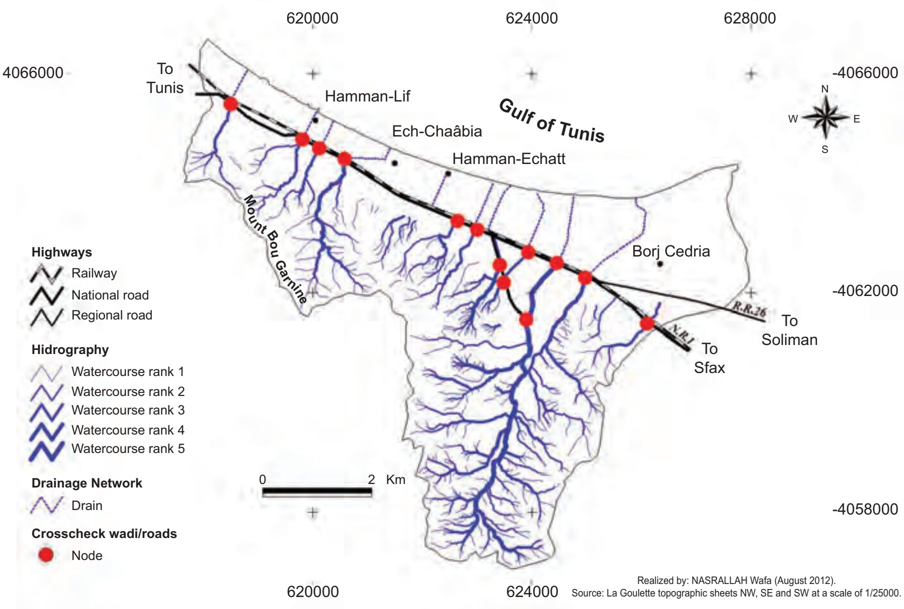


*Figure 6*
*Crosscheck between watercourses*
*and roads in the southern suburbs of Tunis.*

# How to control flood risk?

Faced with the increase in assets in flood-prone areas, the sometimes relative, yet real failure of land use management must be noted. Land demand has been too high and changes in land use too sizeable and rapid to be controlled in risk-prone areas. Land use control tools have been set up, particularly in France but their efficiency has been limited. Moreover, they do not efficiently address the question of existing buildings in flood-prone zones.

Debates tend towards integrated flood risk management, from prevention to post-crisis, via crisis management preparedness and warning devices. However, structural measures (i.e. aiming at controlling flood hazard: dams, dikes, river bed recalibration) remain often the first considered type of response to risk whereas non-structural measures struggle to become widespread, except for warning and crisis management which are increasingly efficient.

## Structural measures are still dominant

The set of flood prevention tools has broadened considerably (Andjelkovitch, 2001), but despite international requirements for comprehensive risk management plans (2007 European Directive; UNISDR, 2005, UNISDR, 2015), the temptation to use structural measures (such as dikes) as the solution to all flood risk problems is still high, whether in Morocco, Algeria, France or Tunisia.

After the Bab-el-Oued floods, the newspaper *Le Quotidien* claimed: "40 million dinars for a protection plan. Bab-el-Oued will never experience another flood". The newspaper article presented projects commissioned or considered by the State to protect Algerian cities from floods. At the same time, new buildings were built (after the disaster of 10 November 2001) such as a primary school in the minor bed of Wadi Koriche in Bab-el-Oued.

For several decades Morocco has relied on a dam building policy (150 great dams storing 18 billion $m^3$ of water), initially designed to fight drought. In these dams, important parts were reserved for flood water reduction.

These works are expensive and do not guarantee 100% protection. They may even be an additional risk factor during exceptional events (dam or dike break). The only 100% efficient prevention method is to refrain from locating vulnerable activities and buildings in flood-prone areas. This may seem obvious but it does not appear to have been incorporated at every level of land use planning.

## The difficult control of land use

Land use control is a fundamental point of risk reduction policies and practices (Pottier et al. 2005). Existing regulations in France (R 111-3, Submersible Surface Plan (PSS)) were rarely applied until the setup of the Exposure to Predictable Natural Hazard Plans (PER in French) in 1984 and the Risk Prevention Plan (PPR in French) in 1995. When these plans are approved, they are generally respected but local authorities sometimes use stratagems to delay their application. The Ministry of Ecology (CGDD, 2009) showed that in 424 French cities, nearly 100,000 dwellings were built in flood-prone areas between 1999 and 2006. Demand is also high from local authorities to urbanize areas "protected" by dikes.

## Living with water?

For the millions of people living in flood-prone areas, living with water is an undeniable fact. In this case, they must adapt existing buildings in order to limit damage costs and ensure the safety of people (Kelman, 2007). In urban renovation areas, there have been attempts to take the risk into account within the redefinition of urban space. Activities are spread out according to their vulnerability, in decreasing order, as the flood hazard increases. Thought has been given to this question (November et al. 2011) and the French Ministry of Ecology has initiated reflections on how to build safely in prone areas (Bonnet & Morel, 2016).

# Conclusion

The information provided by retrospective studies on past evolutions of frequency and intensity of heavy rainfall in the Mediterranean and models developed to anticipate these evolutions in the future is uncertain (Soubeyroux et al. 2015; Tramblay et al. 2012). However, the socioeconomic and demographic human evolutions that the Mediterranean basin has experienced over the last 50 years have proved far more decisive. The land use transformations have constituted a real “risk production process” through the increase and the spatial concentration of exposed assets and the evolution of vulnerabilities.

These land use changes are linked to broader changes in our societies. They are disconnected from the risk issue but they have repercussions for the population’s exposure. They are not only quantitative (rise of assets at risk) but also qualitative. They affect the degree and nature of social and territorial vulnerabilities facing floods. Our societies are not vulnerable in the same way as they were 50 years ago, nor in the same places. The vulnerability of traditional housing (adobe bricks, cob) facing floods is thus reduced by the use of concrete but reappears in other forms (precarious housing) and other places. Conversely, the vulnerability linked to migration increases with the often anarchic densification of networks.

Demographic pressure is not expected to decrease before 2050. It has been forecasted that at this date, there will be near 170 million inhabitants on the European side (versus 140 in 2005) and over 300 million on the east and south coasts of the Mediterranean basin (151 in 2005). Near 2030, around 42 million extra dwellings will be necessary, mainly in cities (source: http://planbleu.org). This will also be followed by the aging of the population including in the South (Coudert, 2002). Research shows that the elderly are more vulnerable in the face of flood risk (Jonkman & Kelman, 2005; Vinet et al. 2012).

Prevention disconnected from the land use control issue is doomed to fail. Above all, the question of flood risk management and prevention is a territorial issue with a heavy social and political resonance. The choices made in this field may determine the risk of future and forthcoming disasters.

While the potential impacts of climate change are certain for some and more hypothetical for others, social and land use evolutions are decisive in the process of risk production. Urbanization, population growth, social transformations, and housing evolution are key parameters in flood risk evolution. Beyond any consideration about climate change, it is urgent to take disaster risk reduction measures – and preferably non-structural measures that are more resilient in the face of climate change.

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Sub-chapter 3.4.2

# Forecast of heavy precipitation events

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## Introduction

Forecasting and managing severe natural hazards are key topical issues, especially when considering the scale of damage, their social and economic consequences and their after-effects. Legal liabilities can only be met by a policy of management of natural hazards and selecting the appropriate means for the appropriate goals.

In the Mediterranean region, intense rainfall events constitute a real danger to the population. Heavy rainfall, sometimes associated with strong winds, can cause floods, particularly during the autumn season, with dire consequences for people and the environment. Although the course of events cannot be changed (from a meteorological point of view), it is now possible to better understand these phenomena and their dynamics and thus to warn the populations of their occurrence from a few hours to several days in advance.

These heavy precipitation events are favoured by the particular local geography of the Mediterranean basin, a nearly enclosed sea, surrounded by mountainous regions. All countries bordering the Mediterranean basin are subject to these severe events, for instance, North Africa with the flash-flood episode, which struck Morocco in December 2006, Algiers in November 2001, frequent episodes along the Spanish eastern coast, in the South of France and along the Italian coast. These natural disasters have been responsible for many casualties and huge economic losses.

Although much progress has been made in recent years in understanding the driving mechanisms behind these systems and in improving their forecast, the precise forecasting of the location of such episodes remains a major challenge. The final quality of the weather forecast depends mainly on three factors. Accurate knowledge of the initial state of the atmosphere is provided by an optimal analysis of recent observations. The second factor consists of expertise able to provide an estimate of the future atmospheric state, which generally comes from a combination of numerical weather prediction models describing the evolution of atmospheric parameters (pressure, wind, temperature and humidity) and of forecasters who interpret model results and translate them into weather-sensitive elements not directly provided by modelling, such as visibility. The third factor represents the meteorological information focus on the end-users' requirements (in terms of communication and information availability).

## Numerical prediction of heavy precipitation systems

Atmospheric dynamics and thermodynamics are relatively complex. Only the use of modelling provides an efficient means to gather knowledge and optimize forecasting and monitoring processes. In many countries, limited area models with a finer spatial resolution than global large-scale models are run daily. One such model is the 10 km resolution ALBACHIR model which simulates the atmospheric circulation over Morocco and is run in real time by the Moroccan weather service, DMN (fig. 1a). A kilometric horizontal resolution, together with detailed initial conditions, has been shown to significantly improve the convection simulation (Ducrocq et al. 2002) and has motivated the design of kilometric-resolution operational models such as the AROME model in Météo-France. AROME is currently run in many countries such as Morocco at a 2.5 km resolution (fig 1b). Since April 2015, the resolution of the French AROME version is 1.3 km and 90 levels (fig 1c, Brousseau et al. 2016), which helps the model to describe more realistic convective cells in terms of size, number, intensity and lifetime.

An ensemble prediction system (EPS) based on AROME (Raynaud and Bouttier, 2016), complementing the deterministic system with a quantification of forecast uncertainties in terms of localisation and intensity, will become operational by the end of 2016 at Météo-France.

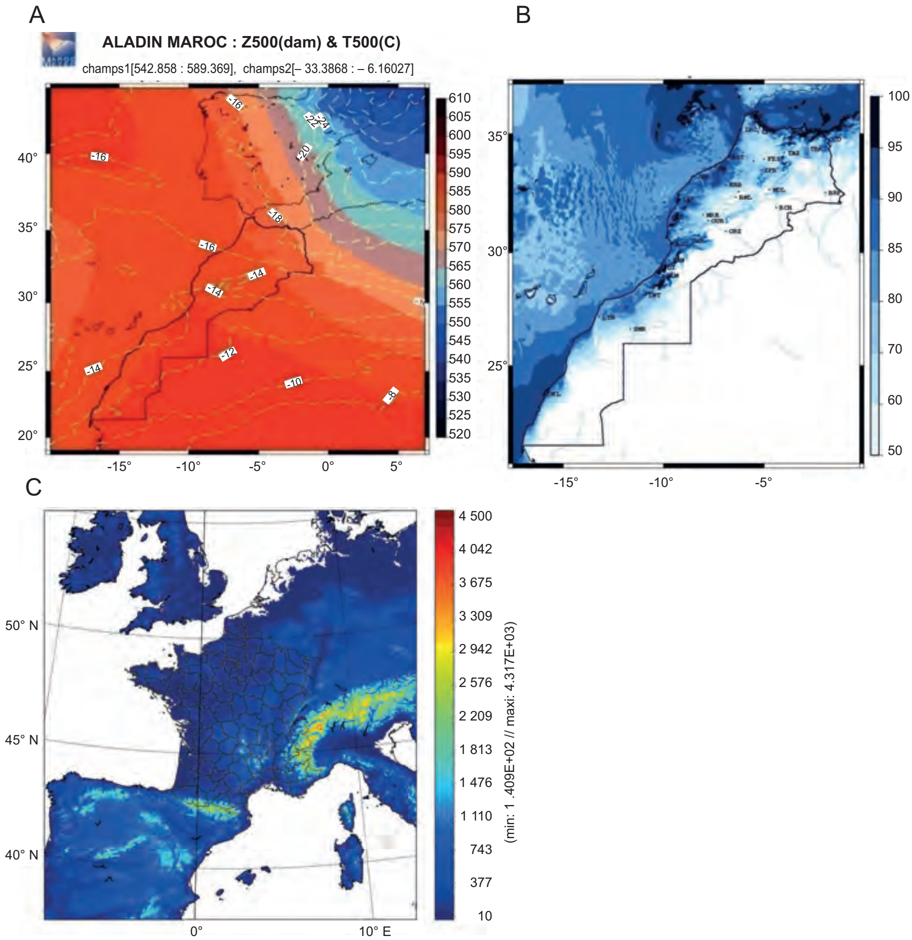


*Figure 1*
*Domains of the operational regional numerical weather prediction models of the Moroccan Meteorological Service ALBACHIR a) AROME-MAROC b) and AROME domain at Météo-France c).*

# Observations and their use in forecast models

Accurate initial conditions, especially in terms of wind and humidity description at low levels and in the mid-troposphere, are necessary for a realistic simulation of key aspects of precipitating systems (intensity and localisation, Ducrocq et al. 2000 and 2002). High-resolution models represent convective cells with significant small-scale memory: specific features from dissipation convection (such as gust fronts or cold pools) may influence the development of new convective systems. In this context, the AROME model may benefit from high-frequency observations, through frequent updates of the initial conditions. These updates are provided using data assimilation which combines information from the model (namely, a short term forecast) and observations. Data assimilation aims to readjust the trajectory of the numerical mode at regular intervals, so that it is the closest to the actual state of the atmosphere at the beginning of the forecast. Algorithms such as variational assimilation are used in many countries and are particularly efficient for handling large numbers of different types of observations. These algorithms provide a corrected initial condition, optimally combining information from a forecast and observations, over the whole model domain. In addition, they allow for the assimilation of many data which are indirectly linked to the model quantities, such as remote sensed data (like cloudy satellite observations or precipitating radar data).

At mesoscale, as it is necessary to have information at a high spatial and temporal resolution, meteorological radars appear to be particularly relevant for characterizing rainy and precipitating events. They can provide wind measurements and reflectivities, delivering information on precipitating hydrometeors at a kilometric resolution every 15 minutes. The cycled data assimilation of joint Doppler winds and reflectivity significantly improved probabilistic forecast rainfall scores as well as the localization of convective cells (Wattrelot et al. 2014). Radar networks have been deployed in many countries. With the acquisition of weather radar (7 Doppler radars), a project to integrate radar data is being initiated for AROME-Morocco (fig. 2).

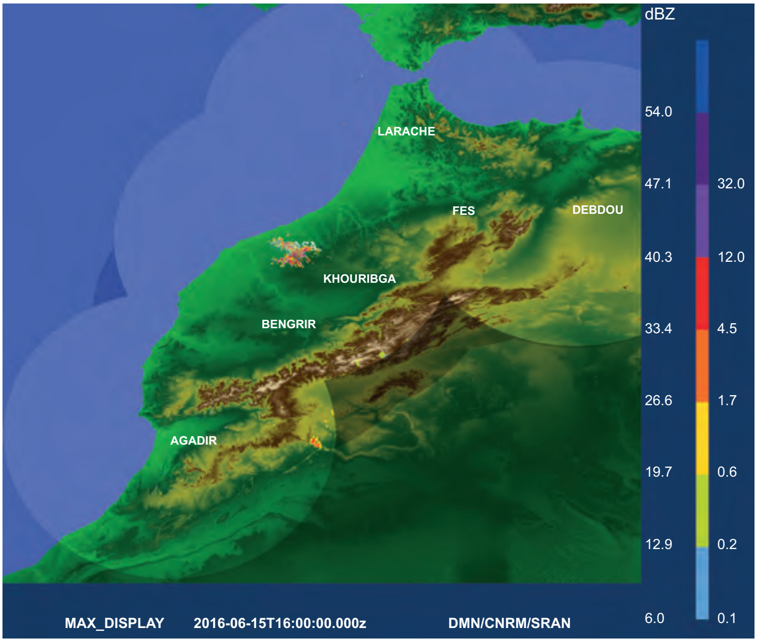


*Figure 2*
*Moroccan radar network.*

At European level, the EUMETNET/OPERA programme aims to promote radar data exchange in Europe. The latest phase of this programme (OPERA4) focused on the preparation and the provision of radar data for numerical weather prediction models. In the context of an experimental campaign, a preliminary study at Météo-France showed the potential benefit in using both Spanish and French radar data together in the initial state of the AROME forecast (fig. 3).



## Vigilance (weather alert) maps and real-time monitoring of heavy precipitation

In many countries, vigilance maps are produced twice a day to warn populations of impending meteorological hazards. They publicize the likelihood of a severe event threatening one or more provinces within the next 24 hours. They are now available in many countries. Two examples are given for France and Morocco respectively (fig. 4). A four-color weather alert code is used to evaluate the risk level. For a very highly probable severe weather hazard, i. e. an orange or red alert, monitoring bulletins are issued as often as necessary. These describe the current phenomenon in progress, its evolution in the coming hours, likely consequences and potential damage and the behaviors to adopt.

For example, the Moroccan weather service, fully aware of its national and international responsibilities, launched the Vigiobs project with a view to improving early warning systems for natural disasters. In the context of this project, significant work has been done on the reliability of the observation network at stake on the quality of the measurement, the concentration of data and supervision of the network. Work tools forecasting services have gradually adapted to incorporate new features implemented in the framework of Vigiobs.

The financial effort made by DMN and the priority given to the Vigiobs network deployment enabled the forecasting services to have a network of ground observations that best meet their needs. The frequency of messages sent by the stations varies between one minute and 24 hours, which can be configured remotely from the central hub, depending on the weather conditions. As a rule, messages are sent every hour. In addition to the Vigiobs surface network, DMN operates a network of seven Doppler radars, three second-generation satellite reception stations and a lightning detection network. These observation systems have enabled better weather condition monitoring in real time and have improved the accuracy and timeliness of warnings.

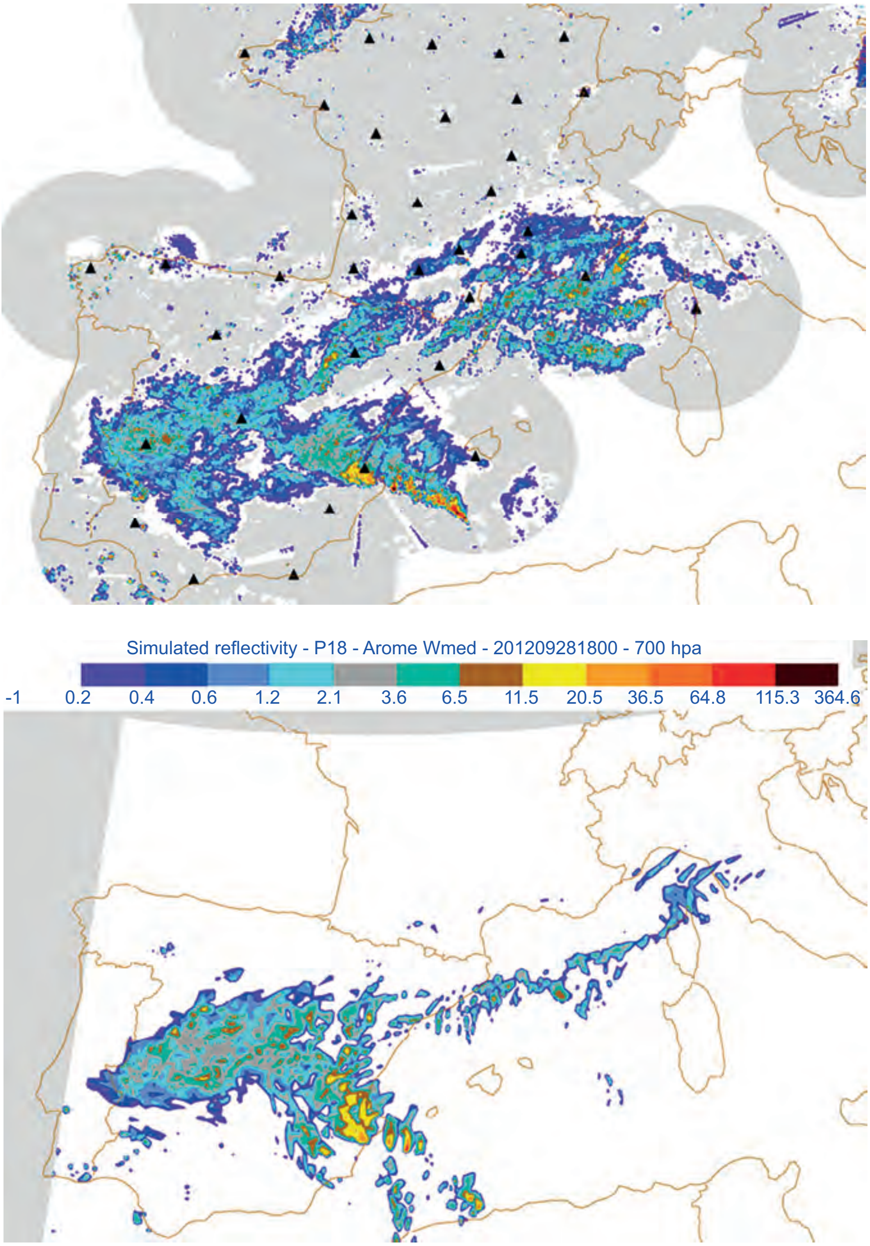


*Figure 3*
*For 28 September 2012 at 18 UTC: a comparison between the observed radar composite in dBz (top) with the location of radar (black triangles) and simulated reflectivities in dBz (at 700 hPa altitude) by the Mediterranean version of AROME, from a 18 hour forecast which assimilates radial winds and reflectivities from Spanish radars (bottom). The legend scale is the same for both images and indicated in equivalent rain rate in mm/h.*

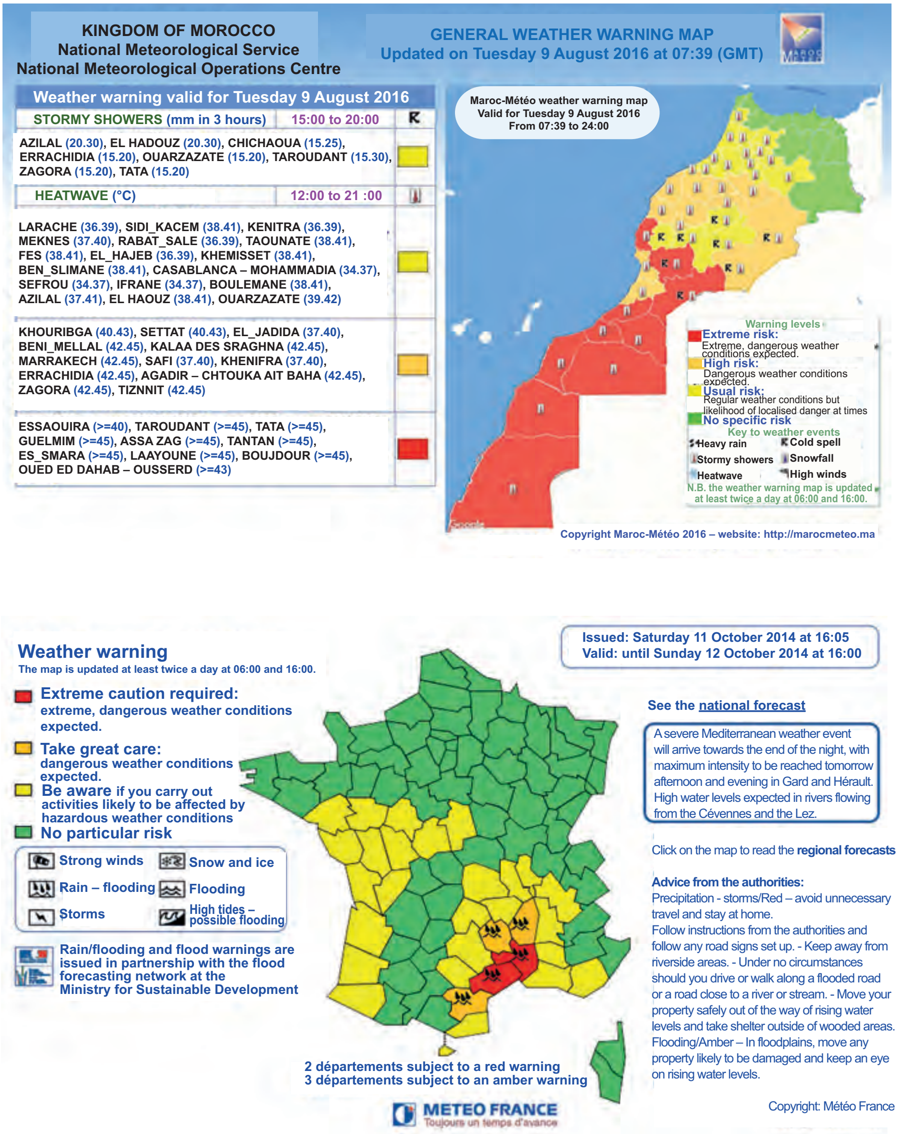


*Figure 4*
*Example of vigilance maps*
*with a four colour scale produced by Moroccan Weather Service (top)*
*and by Météo-France (bottom).*

## Research to better understand and forecast heavy precipitation events

The Hydrological cycle in the Mediterranean Experiment (HyMeX) (Drobinski et al. 2014) is a 10-year international programme. This project aims for a better understanding and quantification of the hydrological cycle and related processes in the Mediterranean Sea. It focuses on high-impact weather events, inter-annual to decennial variability of the Mediterranean coupled system, and associated trends in the context of global climate change. The first HyMeX special observation period (SOP1) took place from 05 September to 06 November 2012 over the north-western Mediterranean Sea including the French, Italian and Spanish coastal regions. SOP1 was dedicated to heavy precipitation and flash flooding (Ducrocq et al. 2014).

This experiment also provided the opportunity to assimilate new observations or improve the assimilation of already existing ones. Studies on the radar parameters distinguishing the dominant hydrometeors, or indirectly linked with low-level humidity, have been conducted and experimental data such as lidar data have been assimilated. Furthermore, this experimental campaign represented a test-bed for future kilometre-scale ensemble prediction systems.

## Perspectives

Progress in modelling of heavy precipitation, flash-floods and vulnerabilities now enables us to consider designing seamless modelling approaches in order to meet societal expectations. Progress is also expected in the coupling of atmospheric, oceanic and hydrological models which will improve heavy precipitation and flash-flood forecasts. For example, the AROME EPS will drive a full hydrological ensemble prediction system for probabilistic flash-flood forecasting and flash-flood warning. In the longer term, improvements of exposure and vulnerability modelling capabilities will enable the coupling of these models with heavy precipitation and flash-flood hazard models towards the development of impact-based prediction models. Such models should help ensure effective responses from decision makers in disaster management.

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# Improving flash flood forecasting and warning capabilities

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## Introduction

The consequences of flash floods can be dramatic in terms of casualties or economic losses. Jonkman (2005), in a global assessment of flood-related casualties, showed that flash floods lead to the highest mortality (number of fatalities divided by the number of affected people). For example, in the recent flash flood that occurred in the French Riviera around Cannes on 3 October 2015, 20 casualties and 650 billion euros of insured damage (source: http://www.ccr.fr/) were reported. Flash flood forecasting systems are critically needed to better organize crisis management and rescue operations.

As mentioned in chapter 1.3.4 (Gaume et al. 2016), flash floods are characterized by a rapid increase of river water levels. They often affect small watersheds, generally ungauged. The spatial and temporal variability of rainfall, landscape characteristics and pre-event catchment wetness are important influential factors in flash flood generation, contributing to the large space-time variability of hydrological responses (Borga et al. 2011).

Forecasting flash floods is therefore a complex task. It necessitates the monitoring of large areas, where each small watershed of a few square kilometres can possibly be affected. Real-time observation networks and models must run at small temporal and spatial scales, covering a few minutes and kilometres. Furthermore, discharge time series are not available for the majority of the possibly affected watersheds, posing a real challenge for model calibration and evaluation. In this context, radar based precipitation products and/or meteorological forecasts with a high resolution (typically 1 $km^2$ grid size) are crucial (Creutin and Borga, 2003). Slight misplacements of the precipitation may for instance lead to warnings attributed to the wrong river network and to inappropriate flood management decisions.

Various approaches exist to forecast flash floods. One of the first proposed approaches is the so-called Flash Flood Guidance (FFG) method (Georgakakos, 1986). It consists of determining *a priori*, based on rainfall-runoff modelling, the amount of rainfall needed to generate bank-full discharge at the catchment outlet, depending on the initial wetness condition. Gourley et al. (2010) reviewed flash flood forecasting methods used in recent decades in the USA. According to their results, distributed hydrologic models forced by radar-based rainfall estimates outperform FFG in predicting discharge threshold exceedances. Several improvements of existing flash-flood forecasting methods based on distributed rainfall-runoff models have been recently proposed. Various tests have been conducted to assess how forecasting lead-time could be increased valuating quantitative precipitation forecasts (Barthold et al. 2015). In particular, some authors considered how uncertainties associated with these precipitation forecasts (intensity and location of larger rainfall cells) could be accounted for, leading to proposals of ensemble precipitation inputs (Velasco et al. 2013; Armengal, 2015) or a perturbation method applied to deterministic precipitation forecasts (Vincendon et al. 2011). A special issue of the Journal of Hydrology, which is about to be published (Braud et al. 2016), will feature ten papers presenting recent advances in flash flood forecasting. This includes the improvement of the FFG method to better account for rainfall spatial variability and initial soil moisture, the set-up of operational systems, the proposal of ensemble and probabilistic flash flood forecasting systems and the test of satellite-derived rainfall fields.

The present chapter focuses on two examples of recent advances in France, illustrating what performances could be achieved in the coming years by improved flash flood forecasting systems. The first example shows how effective flash-flood warnings can be proposed for small headwater streams, based on a simplified 1 $km^2$ rainfall-runoff model fed with rainfall estimated from weather radar data. The system, called AIGA, is running operationally over a large area in the South-East of France (Javelle et al. 2014). The second examples show how the impacts of flash floods can be directly forecasted to help crisis management services identify the areas at risk.

# Highly distributed flash flood warnings: example of the AIGA system

The AIGA method was initially developed for the South of France (Lavabre and Gregory, 2006). Its real-time outcomes have been tested over the last five years, with end-users from the “Provence, Alps, “Côte d’Azur” region in the framework of the RHYTMME project (http://rhytmme.irstea.fr). It will be operationally implemented at the national French level in 2017. The AIGA method is based on a simple 1 km² grid distributed rainfall-runoff model (fig. 1) forced by radar rainfall estimates (fig 2). The model, regionally calibrated and based on about 700 measured discharge series, is presented in greater detail in Javelle et al. (2016). It forecasts future discharge values along the modelled stream networks for all stream reaches with upstream watershed areas of at least 5 km². The theoretical return periods of the forecasted discharges, evaluated on the basis of a calibrated regional flood frequency method (Aubert et al. 2014), are then computed and mapped (fig. 3).

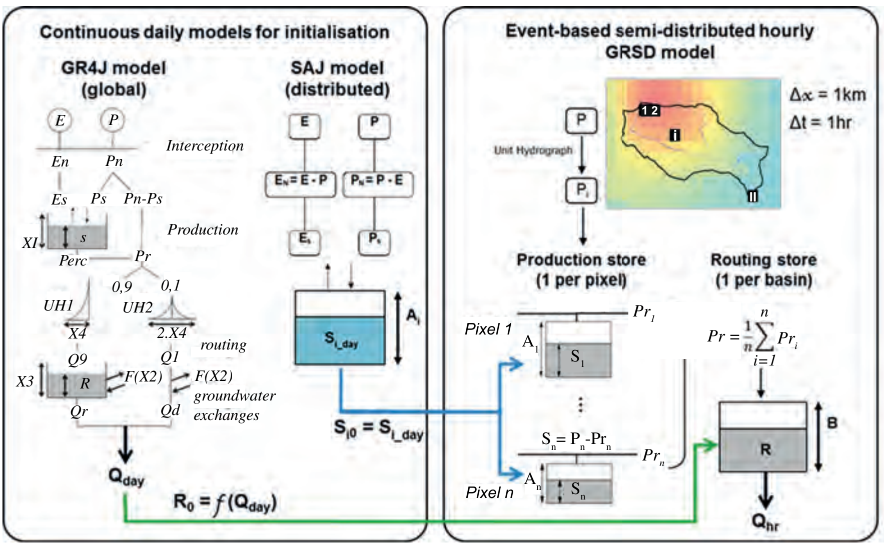


*Figure 1*
*Rainfall-runoff model included in AIGA, with precipitation (P) and evapotranspiration (E) as inputs, and daily and hourly streamflows ($Q_{day}$ and $Q_{hr}$) as outputs (Javelle et al. 2016).*

Two screen snapshots of the RHYTMME platform illustrate the type of outcomes produced by the AIGA method. These figures correspond to a major recent flash flood event which occurred on 3 October 2015 on the French Mediterranean coast which resulted in 20 fatalities and 650 million euros of insured damage. The intense rainfall event affected a narrow coastal and densely urbanized band of about 300 km² (fig. 2). The maximum rainfall intensity was measured in the town of Cannes: 175 mm in 2 hours. The 50-year peak discharge has been exceeded on several small coastal streams according to the AIGA method (fig. 3).

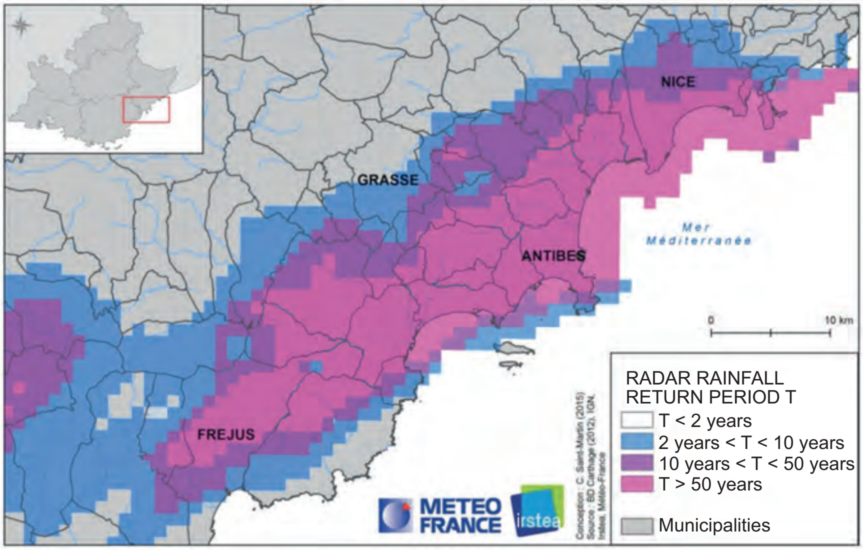


*Figure 2*
*Return period of the cumulative radar rainfall intensities measured on 3 October 2015 (screenshot of the RHYTMME platform).*

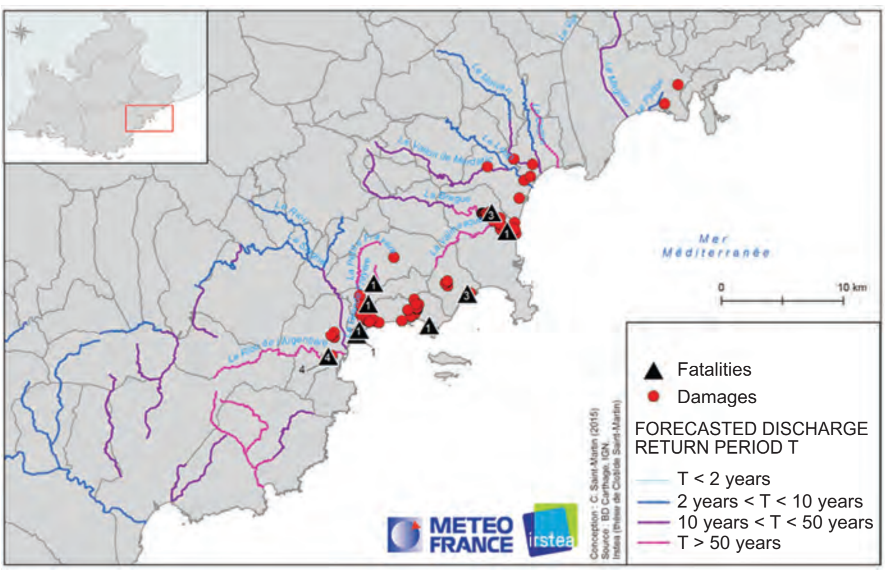


*Figure 3*
*Return period of the forecasted peak discharges for various stream sections for the 3 October 2015 flash flood event (screenshot of the RHYTMME platform).*
*Location of the fatalities and main reported damages after the event.*

An intensive post-event survey was carried out after the event. Peak discharges where estimated at different ungauged river sections. Extensions of inundated areas were georeferenced. The type and location of damage and fatalities were reported based on field witness accounts and a press review. Social networks also proved to be a valuable source of information (Saint-Martin et al. 2016). This post-event documentation helped confirm the accuracy of the forecasts provided by the AIGA system. The overall consistency between the forecasted peak discharge return periods and the location of the fatalities and main damages can be seen for instance in fig. 3.

In its current form, the AIGA method has two main limitations. First, the forecasts are based on radar-estimated rainfall, limiting the forecasting lead-time and event management capacities. Accounting for rainfall predictions could improve the situation. Second, decision makers have to translate forecasted stream discharges or water levels into possible field consequences to organize rescue operations. The forecasting delays leave very little time to conduct this analysis in real time in the case of flash floods. Ideally, forecasting systems should directly provide indications about possible field consequences to better support decision-making processes in flood event management situations. The next section illustrates, that this last objective will probably be attainable in the near future.

## Towards the prediction of the possible impacts of flash floods

Fig. 4 shows one first illustration of the forecast of flash flood possible impacts. The test area is the French Gard department, located in the South East of France. It is the area most frequently affected by damaging flash floods in France: on average one event every year. The objective was to develop a prototype of a warning system to detect road sections at risk of flooding: 2,000 targets (intersections between road and river networks) were identified over an area of 5,800 km². The prototype was based on the combination of (i) a distributed rainfall-runoff model and (ii) a calibrated method rating the susceptibility to flooding of each road/river intersection, to adjust the discharge thresholds at which warnings are generated at each intersection (Versini et al. 2010; Naulin et al. 2013). Warnings and estimated corresponding flooding risk levels were compared to reported inundation of roads for 10 recent severe flash floods (Figure 4). The results proved to be promising. Overall, the method appeared to be efficient in locating the affected area in the Gard department (fig, 4a). The matching between computed risk levels and actually inundated roads was less satisfactory in the affected areas, with high falls alarm ratios due to the difficulty in characterizing a priori the susceptibility to flooding of the intersections (fig. 4b).

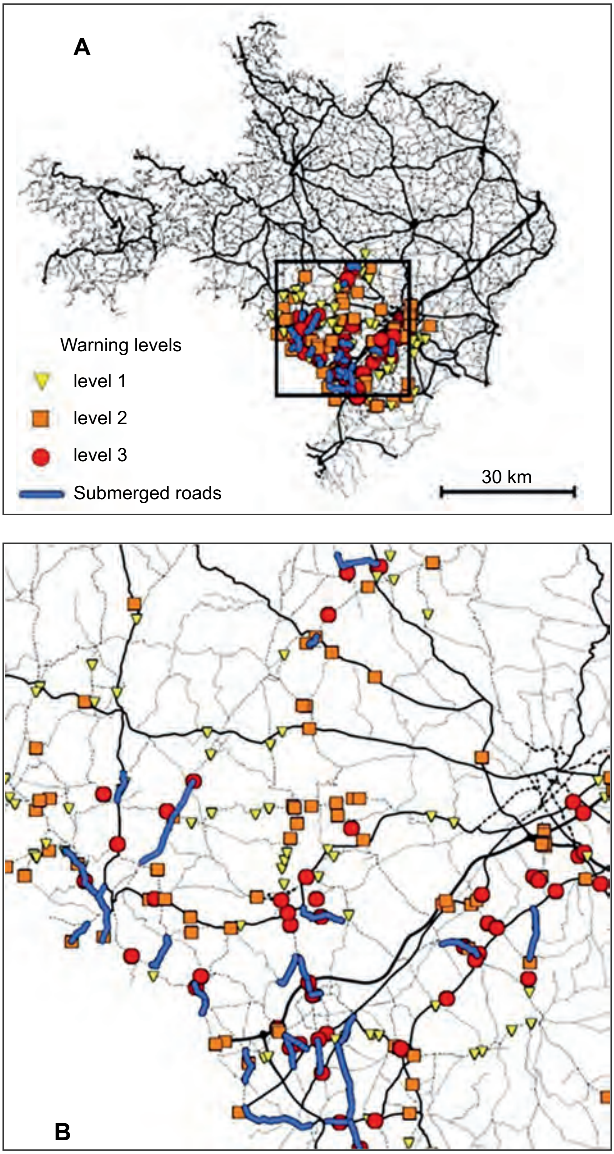


*Figure 4*
*Map of the maximum alarm levels generated*
*by the PreDiFlood road inundation warning system*
*for the 29/09/2007 event. Comparison with observed road inundations.*

In the same line of thought and in the same area, tests are now being conducted to evaluate the extent to which the exiting rainfall-runoff and simple hydraulic computation models are able to correctly forecast the extent of the inundated areas on a large stream network and provide indication about the possible number of affected buildings for each stream reach considered (Le Bihan et al. 2016). The forecasts are tested against insurance claims for this specific application, with promising preliminary results. Fig 5 illustrates the added value of an integrated approach forecasting the flash flood impacts (fig. 5b) when compared to a standard approach providing discharge magnitude forecasts (fig. 5a). The spatial distribution of the problematic stream reaches is clearly different for both methods. Unsurprisingly, local exposure and vulnerability are important drivers of the risk level and should be considered in flood event management.

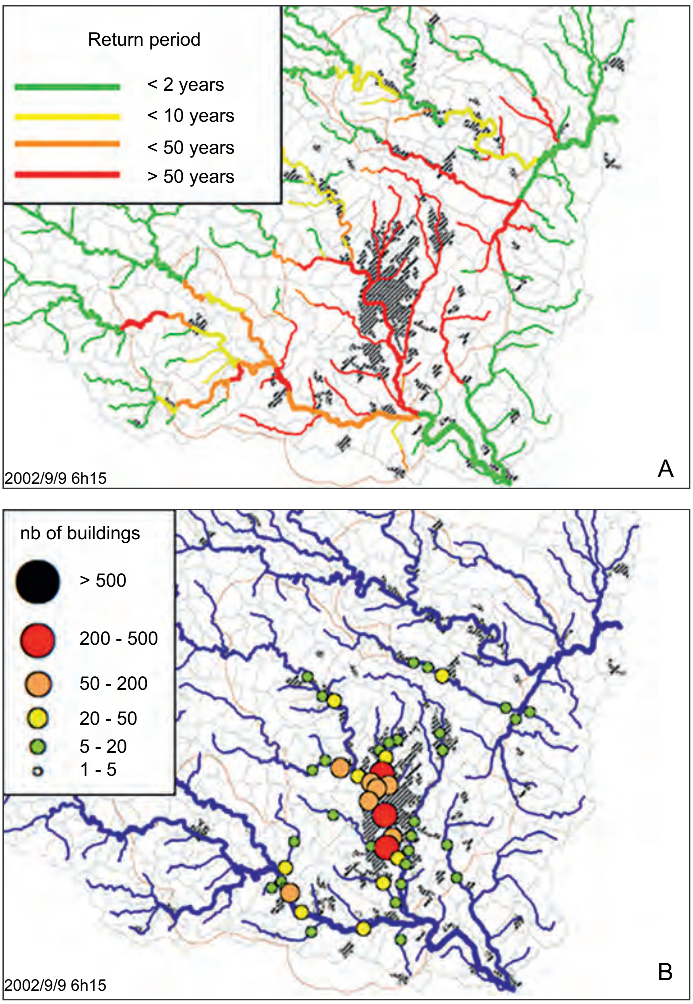


*Figure 5*
*Example of forecasting results obtained for the 08/09/2002 event in the region of Alès (Gard): a) hydrological qualification based on the rainfall run-off model, b) associated impacts estimated (number of inundated buildings).*

# Conclusion and perspectives

Flash flood forecasting is a new, active and innovative research and development activity. Recent advances in term of hydrological modelling and rainfall measurement and forecasting now facilitate the proposal of operational applications and services, but progress is still ongoing as illustrated above. The challenges posed by flash flood forecasting require the development of interdisciplinary approaches merging competences in hydrology, meteorology, hydraulics and social sciences for a better assessment of exposure, vulnerabilities and risks.

If compared to standard flood forecasting approaches in the case of flash floods, the lack of measurements on most of the affected streams and the necessary prediction of flood impacts, imply the development of new approaches and the valuation of new information such as damage for the validation of the forecasts. Every citizen may become a potential observer and the emerging social networks prove to be extremely useful sources of information if correctly used. A new field of research is emerging, on how to collect and check this data (data mining), and how to use it in combination with flood forecasting models. Improved interactions with decision makers and stakeholders that could be affected by flash floods (for instance road or railway network managers, rescue services…) also present an interesting perspective, as these actors are both, possible end-users of the forecasts and data providers.  Remote sensing approaches also now provide information to detect the areal extent and depth of flooding and to support streamflow estimation. Spaceborne platforms yield observations that are typically too infrequent for the flash flood scale, but observation platforms such as UAVs and aircrafts are increasingly being used.

### Acknowledgements

Part of the literature review of this chapter was prepared for the preface of the *Journal of Hydrology* special issue about "Flash Floods, hydro-geomorphic response and risk management" which is in press. The work presented here also contributed to the HyMeX (Hydrological Cycle in the Mediterranean Experiment) program (Dobrinski et al. 2014).

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# Seasonal forecast of droughts and water resources

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## Introduction

Forecasting the upcoming season is a fundamentally different scientific issue from forecasting the weather over the next few days. Due to the intrinsically chaotic nature of the atmosphere, the predictability of temperature, winds, precipitation or pressure systems is typically limited to 10 days. Seasonal forecasts therefore set out to provide an outlook on statistical averages of climatic variables at ranges from one month to a year, and rely on large-scale, more slowly-evolving components of the climate system such as the ocean or land surface. The best known source of climate variability on a seasonal time scale is the El Nino Southern Oscillation phenomenon (ENSO), which occurs in the Tropical Pacific Ocean but has remote impacts on climate variability around the globe. Several approaches are commonly used to produce seasonal forecasts, namely dynamical climate modelling using global coupled models (GCMs), statistical/empirical approaches, or a combination of both.

Dynamical seasonal forecasts are run as ensembles, starting from slightly different initial conditions and/or including in-run perturbations, to take into account initial condition and model uncertainties. These ensembles provide information on the probabilities of occurrence of departures from a mean model climate of the variables of interest. An example of such a forecast, presented as a synthesis plot for tercile probabilities, is shown in fig. 1. The mean climate is estimated by re-forecasting past seasons. These re-forecasts also provide necessary insights into the quality of the forecasting system, and enable the post-processing and calibration of model outputs to extract useful information for end-users.

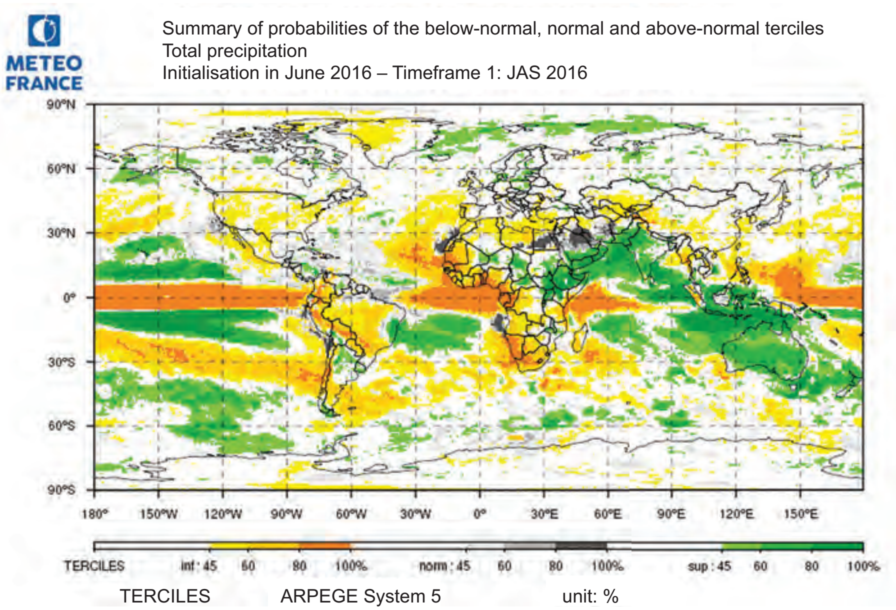


*Figure 1*
*Synthesis plot for July to September 2016 seasonal mean precipitation tercile probabilities based on Météo-France system 5 seasonal forecast initialized in June; the colors refer to the most likely tercile and its probability; the areas in white are where no preferred tercile is found.*
*© Météo-France/DCSC*

A number of international efforts have focused on improving dynamical climate forecasts at the seasonal range. In Europe, several initiatives (e.g. the European Commission funded projects DEMETER, ENSEMBLES and SPECS) have developed multi-model forecasting strategies and studied predictability at seasonal or longer time scales. Seasonal forecasting systems based on coupled dynamical atmosphere and ocean models exhibit skill – with respect to common benchmarks as persistence or a past climatology – mainly over the Tropics, whereas limited skill is found over mid-latitude regions, including most of the Mediterranean basin (e.g. Weisheimer et al. 2011, Doblas-Reyes et al. 2013).

Although the skill of seasonal forecasts is limited, their uptake by a wide end-user community has been encouraged by the Global Framework for Climate Services (GFCS). Over the Mediterranean region, several prototypes of end-to-end climate predictions and services have been developed and evaluated as part of the European Commission FP7 project EUPORIAS. As the region is prone to droughts and water vulnerability, one of the areas of focus for the Mediterranean is water management issues. This sub-chapter provides an overview of seasonal forecasting activities with a focus on these applications, by summarizing results from recent research, highlighting operational activities at Météo-France, the Direction de la Météorologie Nationale (DMN) in Morocco and the Mediterranean Climate Outlook Forum (MedCOF), and discusses future directions.



## Predictability of droughts and water resources

A first essential step in forecasting droughts and water resources on the seasonal time scale is to properly assess the predictability of relevant key climate variables, such as near-surface temperature and precipitation. As previously stated, skill for these variables is limited over the area of interest. However, recent results suggest that ENSO (Manzanas et al. 2014, Shaman 2014) as well as the North Atlantic Oscillation could have some impact on the Mediterranean region climate at on the seasonal rangelevel, therefore opening perspectives for future improvement of dynamical seasonal forecasting systems, and providing the basis of skill for statistical or combined approaches (such as those developed by Guérémy et al. 2011) in impact forecasting.

For specific areas of interest, provided that a sufficient amount of data is available for model training, statistical models based on linear regression or maximum covariance analysis often exhibit considerable skill over a re-forecast period. However, these methods are highly dependent on statistical relationships which, in a changing climate, could be less robust in the upcoming decades.

Land-surface initialization and land-atmosphere coupling in dynamical systems could provide future improvements, particularly over regions around the Mediterranean Sea such as the Balkans (Ardilouze et al. 2016, Prodhomme et al. 2015). The land-surface variables are commonly initialized from model or reanalysis climatology due to the lack of timely gridded observations on the global scale for real-time forecasts. Inter-annual variability of soil conditions may provide a valuable source of predictability for both climate variables and impact indices over regions subject to drought.

Due to the perception of low skill, the uptake of seasonal forecasts by end-users in Europe (and more generally over the Mediterranean region) has been limited up to now (Bruno-Soares and Dessai, 2016). Recent research efforts at Météo-France have focused on demonstrating the feasibility and added value of using dynamical seasonal forecast ensemble outputs as forcing for hydro-meteorological models to forecast river flows and soil wetness indices (see e.g. Céron et al. 2010; Singla et al. 2012; and the RIFF prototype in EUPORIAS, http://riff.euporias.eu/).



# Operational seasonal forecast activities

## Météo-France

Météo-France started real-time seasonal forecasting in the mid-90s and entered the EUROSIP consortium http://www.ecmwf.int/en/forecasts/documentation-and-support/long-range/seasonal-forecast-documentation/eurosip-user-guide/multi-modelwith a coupled ocean-atmosphere system in 2005. As of 2016, Météo-France routinely provides dynamical seasonal forecasts each month as part of the EUROSIP consortium, and in a proof-of-concept phase of Copernicus Climate Change Services (C3S). These forecasts are based on the CNRM-CM GCM (Voldoire et al. 2013), using the ARPEGE-Climate v6 atmospheric component and the NEMO v3.2 ocean model.

Briefings and synthesis maps can then be disseminated to a wide community through the WMO network, as Météo-France is a WMO Regional Climate Center node on long-range forecasting. These are based on information from the Météo-France system 5 but also other models contributing to the EUROSIP consortium, and balanced against the experience of past model performance. Monthly and daily model outputs can feed impact models for specific applications, including providing climatic indices.

## Seasonal forecasts at DMN

Seasonal forecasts have been developed at the Moroccan Meteorological Service (DMN) in order to provide decision makers with information that can help programming activities and works. Due to the importance of precipitation for agriculture and water resources and the different drought periods registered in the country (i.e. 1980-1984, 1990-1994), the need for information on the coming climate state in terms of seasonal precipitation has increased. Furthermore, in the context of climate change (more variability and climate extremes like drought and hot periods), seasonal forecasts are in increasing demand as they present an adaptation tool in the short term.

During a period of about two decades, seasonal forecast developments and activities in Morocco have taken several steps forward, from a single deterministic forecast using uncoupled models to probabilistic forecasts issued from an operational chain including a coupled ocean-atmosphere model. Fig. 2 gives an illustration of the current chain. Each month, an ensemble of 27 potential climate evolutions for the following three months are developed using the French numerical climate model ARPEGE-Climate coupled with the Ocean Model NEMO3.2, atmospheric initial conditions issued from ECMWF (European Centre for Medium range Weather Forecast) and ocean initial conditions issued from MERCATOR-OCEAN (http://www.mercator-ocean.fr). This ensemble is used to generate probabilistic forecasts for tercile categories (above, below and near normal) comparatively to climatology for both precipitations and temperature. When considering meteorological drought, the relevance of precipitation is straightforward but temperatures are also important; a normal season with high temperatures can lead to a reduction in soil water and then a sort of drought (agricultural, hydrological). A dry season in terms of precipitation can have greater negative impacts when it combines high temperatures. Drought forecasts are also conducted by computing a drought index: the standardized precipitation index (SPI) of McKee (McKee et al. 1993, 1995). Fig. 3 shows an illustration of a past forecast for SPI.

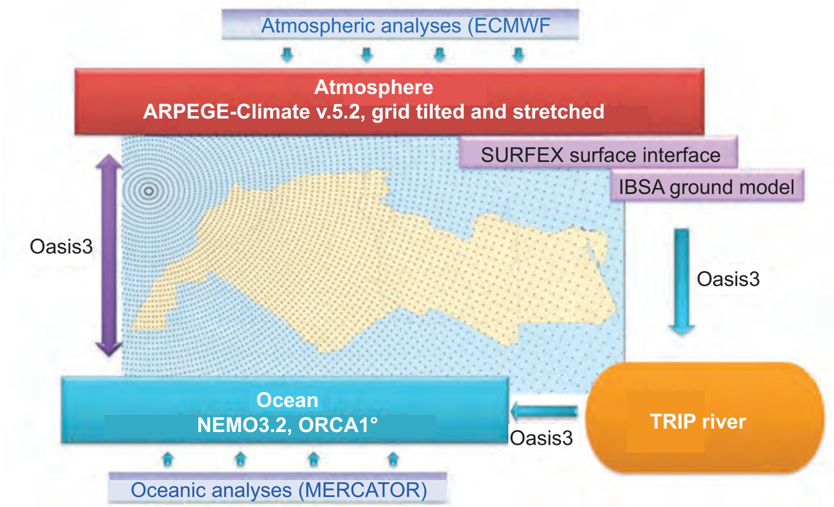


*Figure 2*
*Illustration of the operational seasonal forecast chain at DMN, composed of the ARPEGE atmospheric model, the NEMO ocean model and the TRIP river model, which exchange data using the OASIS coupler.*

Forecast maps for precipitation and temperature are produced and included into the national monthly bulletin along with the SPI bulletin, the outputs of the statistical forecasts also developed at the DMN and other forecasts issued from WMO Global Producing Centers. A forecast statement is given for precipitation and temperature taking into account the different outputs; a way that gives generally more robust forecasts than when using a single model. Seasonal forecasts are also developed each month for the North African Regional Climate Centre (http://rccnara1.marocmeteo.ma/) as the DMN is the node responsible for this activity.

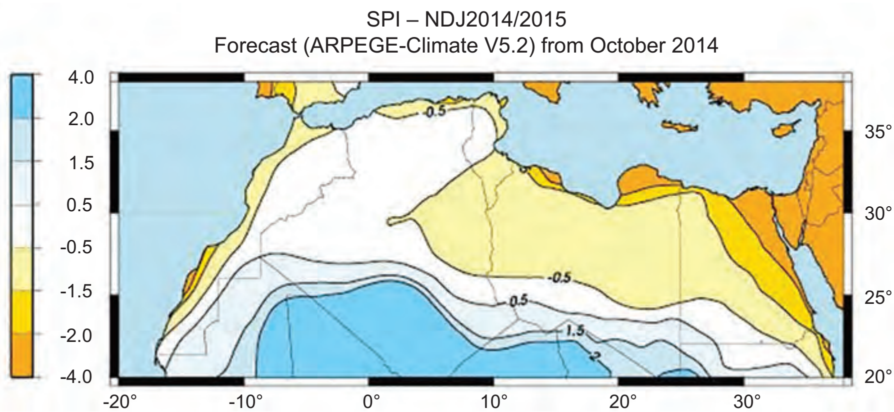


*Figure 3*
*November 2014 to January 2015 seasonal SPI forecast issued in October 2014, based on the ARPEGE-Climat – NEMO coupled system at DMN. The SPI is based on the probability of precipitation for any time scale. The probability of observed precipitation is then transformed into an index. It is being used in research or operational mode in more than 70 countries. Many drought planners appreciate the SPI's versatility. It is also used by a variety of research institutions, universities, and National Meteorological and Hydrological Services across the world as part of drought monitoring and early warning efforts. (Standardized Precipitation Index User Guide)*

Beyond these bulletins, seasonal forecast activities include multisector works and studies that aim to develop and enhance appropriate use for the seasonal forecast by stakeholders, in order to allow them to take full benefit of climate information at a seasonal time scale. As an example, we can cite the recent initiative designed to include forecast meteorological parameters into a crop model and elaborate crop yield predictions. Such kinds of forecasts can help anticipating appropriate actions in case of drought and also be used for optimizing stock importation.

## MedCOF

Following in the footsteps of previously established Climate Outlook Fora, and in order to promote interactions and collaborations across the Mediterranean basin, the Mediterranean Climate Outlook Forum (MedCOF, http://medcof.aemet.es) was started in 2013 and holds outlook meetings twice annually, as well as training workshops.

This forum acts as a platform for potential stakeholders over the region and provides consensus forecasts twice a year based on participating National Hydrometeorological Services (including seasonal forecast providers) and research institutes.

# Future directions

Future research, in the context of international collaborations, is set to focus on several aspects: improving the understanding of local and remote (via teleconnections) sources of predictability over the Mediterranean region; further assessing the skill of current forecast systems in a user-relevant setting; extracting the relevant signal from noise in ensemble forecasts; improving targeted applications by developing cutting-edge downscaling methods. Progress in these areas will rely on the continued integration of the different actors in the climate services chain, from seasonal forecast providers to end-users.

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Chapter 5

# Land degradation and climate change

## What challenges?

Chapter coordinator

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## Abstract

This chapter sets out to present a short review of (i) the general context of land degradation under the framework of UNCCD – the international convention on desertification with a specific focus on Land Degradation Neutrality, and (ii) examples of the main processes responsible for soil degradation (e.g. surface crusting, runoff and water erosion, tillage erosion, wind erosion, and salinization), along with the principles of desertification control and land rehabilitation, in light of the socioeconomic context and ecological conditions and processes. It also focuses on two other key considerations for land restoration: the conservation/increase of soil carbon stocks (see Tunisian example), and the biological restoration of functioning soil through the management of mycorrhizal fungi.

Although there is plentiful scientific evidence for strategies to prevent land degradation and/or restore degraded land, new knowledge is needed to step up the fight against land degradation and allow Mediterranean ecosystems to deliver appropriate sustainable services. This chapter cites examples of these scientific gaps (e.g. sensitivity of soil organic matter to temperature increases, the dynamics of inorganic carbon and deep soil organic, and the most effective Plant-AM in ensuring the success of restoration programmes).

# Résumé

L'objectif de ce chapitre est de présenter un bref aperçu i) du contexte général de dégradation des terres dans le cadre de la Convention des Nations unies sur la lutte contre la désertification avec un accent particulier sur la dégradation neutre des terres, et ii) quelques exemples des principaux processus responsables de la dégradation des sols (par exemple, l'encroûtement de surface, les eaux de ruissellement et de l'érosion de l'eau, l'érosion du travail du sol, l'érosion éolienne, salinisation), et les principes de lutte contre la désertification et la réhabilitation des terres, compte tenu des conditions et des processus écologiques, et le contexte socio-économique. De plus, ce chapitre met en lumière deux autres aspects pour la restauration des terres qui sont le maintien/l'augmentation des stocks de carbone du sol (voir l'exemple des stocks des sols en Tunisie) et la restauration biologique du fonctionnement des sols par la manipulation des champignons mycorhiziens.

Bien que les preuves scientifiques sont déjà disponibles pour aider les stratégies visant à prévenir la dégradation des terres et/ou à restaurer les terres dégradées, de nouvelles connaissances sont nécessaire pour intensifier les moyens de lutte contre la dégradation des terres et permettre aux écosystèmes méditerranéens de répondre aux enjeux de développant durable. Ce chapitre aborde quelques exemples de ces fronts de science (sensibilité des matières organiques des sols à l'augmentation de la température, dynamique du carbone inorganique, et du carbone stocké dans les horizons de profondeurs, choix des plantes et de leur hôte mycorhiziens adaptés aux conditions locales, valorisation des ressources végétales locales...).


# Introduction: adaptation, resilience, conservation of resources and prevention

Under the framework of UNFCCC, the Paris agreement (December 2015), in place of the almost expired Kyoto Protocol, aims to limit the increase of the global temperature to below 2°C. Article 2.1 stresses the need "to strengthen the global response to the threat of climate change, in the context of sustainable development efforts to eradicate poverty", including actions aimed at "increasing the ability to adapt to adverse impacts of climate change and foster climate resilience and low greenhouse gas emission development, in a manner that does not threaten food production." The need to pursue mitigation and adaptation in tandem is therefore widely acknowledged.

Although humankind has always adapted to diverse weather and climate conditions using a wide range of practices (irrigation, water management, crop diversification, etc.), there is an urgent need to take action to consolidate and accelerate adaptation strategies, particularly in agriculture. This need is borne out by the following factors (Howden et al. 2007):

- A 0.1°C increase in world temperature during the past decade,
- More rapid than expected climate change because of increases in greenhouse gas (GHG)
- Lack of agreement for the reduction of GHG emissions.

Although adaptation has different meanings in ecology, climate policy and evolutionary biology (see Glossary IPPC, 2014), a broad definition would be "an adjustment to actual and expected climate conditions to reduce the risk and vulnerability of ecosystems and society and to seek opportunities to cope with climate change". Adaptation strategies must be formulated in response to well identified risks and vulnerabilities[1]. Two main categories of adaptation can be identified:

- Ecosystem-Based Adaptation (EBA) is the use of biodiversity and ecosystem services as part of an overall strategy to help people adapt to the adverse effects of climate change (SCBD, 2009),
- Community-Based Adaptation (CBD) refers to the participatory identification and implementation of community-based development activities that strengthen the capacity of local people to adapt to climate change (see in Archer et al. 2014).

Africa is the world's second most populous continent after Asia. Most African regions have faced an increase in extreme temperature (Seneviratne et al. 2012). Toward the end of the century, heat waves and extreme temperatures will increase whereas – except in East Africa – projected heavy precipitation will not increase. Observed and projected data lack sufficient scope.

Africa as a whole is the most vulnerable continent due to its high exposure and low adaptive capacity. Because of the lack of observations, the detection and attribution of observed climate change in Africa to anthropogenic emissions is not sufficiently clear-cut (Niang et al. 2014). This therefore reduces the effectiveness of any adaptive strategy, although action is urgently needed. Agriculture – the main economic domain in terms of employment – has witnessed stagnant yields relative to the population growth (FAO, 2002). Recent improvements (2000-2010) have not impacted significantly on the overall pattern, since they have been recorded from the lowest productive countries. Reliance on rainfed crop production (98% of the production relied on rainfed crops un SSA), high intra- and inter-seasonal climate variability, recurrent droughts or floods and persistent poverty limit the capacity to adapt. Africa's food production

1. « The propensity or predisposition to be adversely affected » (IPPC, 2014)

is therefore at risk. Simulations of main crop yields point to the consistently negative effect of climate change on major cereal crops in Africa. A study by Eid et al. (2007) stressed the high vulnerability of wheat production in North Africa. The temperature increases in West Africa are estimated to counteract the positive impact of rainfall increase (Sultan et al. 2013).

Climate uncertainties, lack of real-time and future climate projections, and complex interacting barriers at local, national and international levels need to be addressed to build long term and multi-scale adaptive plans for actions. The National Adaptation Plan for Action (NAPA) and the Comprehensive African Agriculture Development Program (CAADP) highlight the political will to enrich economic growth through agriculture. CAADP focuses on four pillars: land and water management, market access, food supply and hunger and agricultural research (NEPAD, 2010). For Africa, reduced crop productivity has been identified as one of nine key regional risks (Niang et al., 2014).

Research has demonstrated that no single adaptation can meet the needs of all communities in Africa. Moreover, adaptation and mitigation must be integrated in policy. For agriculture, sustainable land management techniques are particularly vital for Africa. This chapter explores the situation with a particular focus on soil functioning. It sets out to present a short review of (i) the general context of land degradation under the framework of UNCCD – the international convention on desertification with a specific focus on Land Degradation Neutrality, and (ii) examples of the main processes responsible for soil degradation (e.g. surface crusting, runoff and water erosion, tillage erosion, wind erosion, and salinization), along with the principles of desertification control and land rehabilitation, in light of the socioeconomic context and ecological conditions and processes. It also focuses on two other key considerations for land restoration: the conservation/increase of soil carbon stocks (see Tunisian example), and the biological restoration of functioning soil through the management of mycorrhizal fungi.

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Sub-chapter 3.5.1

# Land degradation neutrality

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## Land degradation, desertification and land degradation neutrality: definitions

Land degradation is a threat to sustainable development. The term refers to both:

- The decline in biological and/or economic resilience of land when exposed to stress and/or perturbations and
- The loss of the land's adaptive capacity to support basic ecosystem functions (primary productivity, nutrient recycling) after a stress or a perturbation.

The effects of land degradation extend far beyond local or regional scales, because of: a) the connections within the ecosystem – e.g. loss of biomass through vegetation clearance and soil erosion, produces greenhouse gases that contribute to global warming and climate change; and b) the connection between the ecosystem and the sociosystem, e.g. loss of soil and land (in quality, quantity, accessibility), through soil erosion and/or lack of soil restoration, rehabilitation or reallocation, results in land abandonment that contributes to urban migration and/or international migration.

Land degradation is caused by multiple drivers. The various processes involved (alone or in combination) include those generated by human activities (i.e. water and wind erosion, overcultivation, overgrazing, inappropriate uses of natural resources (uprooting of woody areas and excessive clearing). During the 20$^{th}$ century, land degradation has accelerated as a result of the increasing and combined pressures of agricultural and livestock production, urbanization, deforestation, land grabbing, and extreme weather events such as droughts. Land degradation results in each place from an original combination of biophysical, social, economic and political factors.

Although land degradation can occur in any climatic zone, land degradation in arid, semi-arid and dry sub-humid areas[1] is referred to as "desertification". These drylands represent about 41% of the total surface of worldwide terrestrial ecosystems. It is estimated that 10% to 20% of drylands are affected by land degradation (MA, 2005), with severe and extensive desertification in Africa and in Asia. The 2 million or so people who inhabit the drylands suffer from the lowest human well-being and the highest poverty (Thomas, 2008). Nevertheless, drylands provide a wide range of commodities. For example, cotton provides about 30% of annual incomes from export for Burkina Faso, and for Mali (Reed and Stringer, 2016). However, land productivity relies on natural resources there more than in any other region in the world. In these zones, productivity, largely dependent on precipitation, is strongly affected by climate change. It is thought that up to 50% of the Earth's surface will face frequent droughts by the end of 21$^{st}$ century under a "business as usual" scenario. Drylands in northern Africa and southern Europe are likely to become dryer. A potential increase of 1-3°C in drylands (if $CO_2$ concentrations reach 700 ppm) would result in an increase in the evapotranspiration by 75-225 mm per year (Burke et al. 2006; D'Odorico et al. 2013)

The following statement: "[there is a] need for urgent action to reverse land degradation. In view of this we will strive to achieve a land degradation neutral world…." (paragraph 206 of "The future We want", Rio+20, 2012) sets the goal for maintaining a world where the total amount of degraded land remains constant. In 2015, UNCCD defines "Land Degradation Neutrality" (in areas affected by desertification) as a "state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems". This could be achieved by a) sustainable management of land to reduce the rate of degradation; or b) increasing the rate of restoration of degraded land, so that these two trends converge to a zero net rate of land degradation. Very recent publications (see Chasek et al. 2015; Grainger, 2015) have examined the bottlenecks and assessed the feasibility of the operationalization of LDN.



1. Ratio of annual precipitation to potential evapotranspiration within the range of 0.05 – 0.65.

**Box 1**
**Policy context**

The Agenda 21 at the Earth Summit in 1992 at Rio de Janeiro was an opportunity to address the various domains for sustainable development:

• The Convention on Biological Diversity (CBD) targets "the conservation of biological diversity the sustainable use of its components and the fair and equitable sharing of the benefit arising out of the utilization of genetic resources" (for more detail, see https://www.cbd.int/doc/legal/cbd-en.pdf)

• The Convention on Climate Change (UNFCCC) targets the "stabilization of greenhouse concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system…" (for more detail, see http://unfccc.int/files/essential_background/convention/background/application/pdf/convention_text_with_annexes_english_for_posting.pdf)

• The Convention to Combat Desertification (UNCCD) aims "to combat desertification and mitigate the effects of drought in countries experiencing serious drought and/or desertification, particularly in Africa, through effective action at all levels, supported by international cooperation and partnership arrangements, in the framework of an integrated approach which is consistent with Agenda 21" (for more detail, see http://www.unccd.int/en/about-the-convention)

There are obvious links between these 3 Rio Conventions. For example a special report on "Climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems will be drafted for the 6th IPCC assessment report, and in 2015 IPBES launched an assessment of land degradation and restoration (global status and trends in land degradation and state of current knowledge). At the crossroads of these 3 Conventions, soils and organic carbon stocks play a key role in strengthening a triple gain in mitigation, adaptation and food security solutions. The recent adoption of the 17 Sustainable Development Goals (September 2015, https://sustainabledevelopment.un.org) by the United Nations reinforces the "nexus" Food security (SDG 2), Land Degradation (SDG 15) and Climate Change (SDG13).

**Box 2**
**The French Scientific Committee on Desertification (CSFD)**
**http://www.csf-desertification.eu/**

Launched in 1997 by the French Ministry of Foreign Affairs, the Ministry of Ecology and Sustainable Development, and the Ministry for Higher Education and Research, CSFD is an independent multidisciplinary committee (20 members from the main French scientific research institutions) providing policymakers and civil society stakeholders in France and affected countries with updated science-based evidence of causes and impacts of desertification (http://www.csf-desertification.eu/dossier contains examples on "Carbon in dryland soils", and "Ecological engineering for sustainable agriculture in arid and semi-arid West African regions"). CSFD is actively involved in several networks, e.g. "DesertNet International"

## Box 3
## Operationalization of land degradation neutrality (LDN)

An estimated US$40 billion annually is attributed to land degradation worldwide. Additional costs resulting from, for example, increased fertilizer use and loss of biodiversity must be taken into account. Degraded land is costly to reclaim and, if severely affected, may no longer provide a range of ecosystem functions and services, with a loss of goods and many other potential environmental, social, economic and non-material benefits that are critical for society and development.

Strategies to implement the LDN scheme are organized in five steps (Chasek et al. 2015):

• Step 1: **Scoping scale and domain**: although the ambition of LDN is to address global issues, since local land degradation directly affects land inhabitants, any plan for LDN actions needs to determine the spatial scale and the thematic domain targeted,

• Step 2: **Mapping degradation**: Monitoring the implementation of LDN (Step 5) necessitates the definition of baselines. This means classifying and mapping the lands in the areas where LDN is to be achieved, i.e. the identification of lands already degraded and lands under degradation, but also lands not degrading – the difficulty being to differentiate these states along a continuum.

• Step 3: **Prescribing relevant practices**: Good practices in sustainable land management (SLM), when implemented in a given context, lead to improved land management performance. Several criteria determine whether a practice is a good or relevant one. Several regional or international initiatives focus on guidelines and best practices, but more should be done particularly in terms of:

- Stakeholder knowledge brokering systems to share best practices.
- Economic valuations of the best practices.

Practices which do not degrade the land, or which reduce or fight against degradation are relevant if they are targeted and appropriate to the context and to the state of the land degradation, accepted and fair according to the points of view of all stakeholders. That means:

– They should take into account the specificities of the place and its connexion with its immediate (local) and global environment.

– They should be appropriate to the type and severity of the damage, taking into account the the intrinsic characteristics of the place, the climate and human activities, the temporal dynamics and the spatial diversity of the degradation, the multifunctionality of landscapes and the diversity of stakeholders.

– They should be built with several stakeholders and based on experienced practices (e.g. zaï, cordon pierreux).

– They should promote a judicious combination of practices (e. agroforestry, agroecology, integration of agriculture and livestock practices), and their integration in existing exploitation and territorial systems.

– They should be applied without taking the risk of affecting other areas or systems near or far , and within a legal framework.

• Step 4: **Monitoring**: Earth Observation, Official Statistics, with supported by survey sampling/grounds measurements and citizen sourcing will be used to monitor, detect and validate the changes in the sub indicators. Several international and regional organisations

(FAO, OSS, JRC, NASA, ESA) have developed a methodology (land cover classification system) and databases that could be used. One of the key ways to ensure effective LDN monitoring is to set up baselines on land cover information, land productivity and for carbon stocks to determine the initial status of the sub-indicators. The challenge is therefore to use appropriate indicators. In line with SDG target 15.3 and to monitor progress, the indicator: "the percentage of land that is degraded over total land area", is being considered by international organizations (UNCCD, FAO, CBD) and would be based on the use of three metrics:

- Land cover and land cover change
- Land productivity
- Carbon above (plant biomass) and below (soils) stocks

The resulting indicators will allow countries to focus on the relevance and effectiveness of current land and planning policies and agricultural practices.

This monitoring approach should be accompanied by local and participatory initiatives including a broad range of stakeholders. Countries will also need adequate capacity building in data interpretation and validation and their use to inform national authorities and international reporting.



### Box 4
### LDN Fund

In order to achieve Land Degradation Neutrality (LDN) by 2030, an independent fund – the LDN Fund project – was announced during UNFCCC COP 21 in Paris. The LDN Fund intends to raise capital from public and private institutions and to directly or indirectly finance initiatives that promote land rehabilitation and sustainable land management in all countries. The Fund will adopt a collaborative approach, complementing and leveraging existing initiatives. It is expected to partner with other fund managers and financial institutions, including local banks and microcredit agencies to increase scale and impact. Some concerns regarding the Fund's orientation (restoration vs degradation, land status) and structuration (funding platform model, civil society involvement) have been expressed by various partners. Discussions are still on-going during the first semester of 2016 and it is expected that the fund will become operational by the end of 2016

### Box 5
### LDN Action Plan

Following its initiative "Towards achieving Land Degradation Neutrality: turning the concept into practice" with 15 countries, UNCCD secretariat has launched a LDN Target Setting Programme (LDN TSP), designed to help countries familiarize themselves with the methodological and operational LDN approaches and to support countries (technical guidance and expertise, capacity building) in defining baselines related to the LDN indicator and set LDN targets. More than 80 countries are already involved in this programme. Analysis of LCD National Action Plan of should be also undertaken to identify the key points (legal, scientific, governance) where synergies with LDN could be implemented.

### Box 6
### Soil carbon stocks: the Food Security (SGD 2) – Climate Change (SDG 13) – Land degradation and desertification (SDG 13) nexus

At the COP 21 in December 2015 in Paris, Stéphane Le Foll, the French Minister of Agriculture, launched an international initiative called "4 per 1,000, soils for food security and climate change" (see https://youtu.be/JMWpPfhJVzc). This expresses at the global scale the ratio of annual $CO_2$ increase in the atmosphere (4.3 billion tonnes of C on average over the period 2004-2013) and soil carbon stock up to 30 cm deep (about 800-1,000 billion tons of C). It illustrates the fact that land management practices are key to global GES mitigation (SDG 13). Above and beyond the benefit that storage can represent in the fight against the accumulation of greenhouse gases, soil organic carbon is one of the main indicators of the quality and fertility and hence productivity, which is essential for food security (SDG 2). In family agriculture in LDCs, the management of organic materials (crop residues, crop-livestock integration, recycling organic urban waste, etc.) is at the center of farmer practices to maintain or improve yields and fight against land degradation (SDG 15), particularly soil erosion. Their management also helps overcome the scarcity of mineral fertilizers, which are only partially available and certainly less accessible to farmers.

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# Soils and desertification in the Mediterranean region

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## Introduction

The Mediterranean region – and more specifically North Africa – have been subject to climate change throughout the period 1860-2005 (Mariotti et al. 2015). Simulations predict an average rise in annual temperatures of more than 2°C with more intense heat waves. Precipitation is projected to decrease compared to 1980–2005 especially in Spain, Morocco, Tunisia and parts of the Middle East region. This is expected to modify soil temperature and soil water content, and consequently pedoclimate. Desertification processes can increase not only due to climate change and population growth but also as a result of ever more pronounced edaphic aridification processes (Floret and Pontanier, 1984).

In the Mediterranean zone, soils are usually much shallower than in the humid tropics and the temperate zone where pedogenesis is faster and erosion less ancient. In some part of the Mediterranean region, accelerated erosion was initiated several thousands of years ago (Butzer, 2005). Shallow soils with low nutrients and water storage capacity are a major constraint to natural vegetation and crop cover, which in turn affords a weak protection to soils from water and wind erosion.

The objective of this paper is to present a short review of (i) the main soil degradation (i.e. desertification) processes in the Mediterranean zone including water, wind and tillage erosion, and salinization; (ii) some soil management principles to combat land degradation and favour soil rehabilitation.



## Main processes and factors of desertification: surface crusting, runoff and water erosion

Due to water scarcity, which limits biomass production, the soil organic matter of arid and semi-arid zones remains low, especially in sandy soils. As a result, exposed layers have low structural stability and physical crusts develop rapidly even under low quantity of rainfall (Valentin and Bresson, 1992). These crusts reduce infiltration and favour runoff (Podwojewski et al. 2011) even when these physical crusts are colonized by cyanobacteriae (Malam Issa et al. 2011). They also tend to promote sheet erosion and gully erosion downhill (Valentin et al. 2005). These crusts can be destroyed by trampling and tillage (Bertrand et al. 2014) but form again rapidly under rainfall.

## Tillage erosion

Tillage erosion is the downslope displacement of soil through tillage. It mainly affects steep and convex slopes (Kosmas et al. 2001) and is often expressed by lighter-coloured soils than adjacent downhill soils (Photo 1). Due to the often steep cultivated slopes in the Mediterranean region, soil loss rates due to tillage erosion cannot be neglected (Benmansour et al. 2013) especially where tillage started a few thousand years ago (Butzer, 2005). Tillage erosion is therefore one of the major contributors to the variation of soil depth and properties in Mediterranean agricultural landscapes.

*Photo 1*
*Tillage erosion evidenced by light coloured truncated soils, Mateur, northern Tunisia. Tillage erosion is a cumulative process and can have been initiated over on thousand years ago in this region.*
*C. Valentin.*

# Wind erosion

Wind erosion is a threat in the arid areas of the Mediterranean region where the wind is often strong and the vegetation sparse. The type of soil also plays a major role since the most sandy soils are also the most prone to wind erosion (Khatteli 1996) whilst, due to low runoff volume and velocity, sheet and gully erosion remain limited. No coarse fragments increase the surface roughness of sandy soils, and the physical crust that develops when it rains does not significantly decrease wind erosion (Rajot et al. 2003), unlike crusts developed on more loamy soils (Belnap and Gillette, 1998). On the other hand, these sandy soils are the most efficient in stocking available water for plant growth (Floret and Pontanier 1984) so that, in undisturbed conditions, the vegetation cover that develops creates effective protection against wind erosion. Wind erosion increases when vegetation cover is decreased. As an example, soil losses reach very high levels when vegetation is removed a part of the year for cereal cropping (Houyou et al. 2014, Abdourhamane Touré et al. 2015). In olive groves, soil is kept bare by regular tillage to stop the vertical connectivity of pores and limit the capillary rise of residual soil moisture of the deeper horizons. Tillage severely depletes soil organic matter content. This favours the formation of microdunes high enough to render ploughing difficult (Photo 2). For the same type of soil, the type of plough used has also a significant effect on soil losses (see Bergametti et al. in this volume). Human activities currently create unsustainable levels of wind erosion on sandy steppe rangelands, which should incite policy makers not to allow their cultivation.

*Photo 2*
*Olive grove on sandy soil, just after rainfall, region of Medenine,*
*South of Tunisia, the dunes, up to 2m height, appeared after ploughing of the sandy soil.*
*G. Hovhannissian.*



# Salinization

Salinization develops in time and space due to the gradual accumulation of soluble salts – whatever their nature – in or near the soil surface (saline crusts or efflorescences). Some salts, especially sodium salts, favour clay dispersion, degrade soil structure and hamper water infiltration. The processes of soil salinization and sodication are complex, occurring at all latitudes and in all climates, and are closely linked to the flow processes of surface and ground waters (Ghassemi et al. 1995; Montoroi et al. 2002; Hamdi-Aissa et al. 2004; Ali et al. 2016). Many natural factors generate soluble salts and their concentration (weathering and dissolution of rock and soil minerals, geothermal sources, decomposition of dead organisms, drying wind), transport (rain, rivers, groundwater, sea water, wind) and accumulation in soils (arid climate, temporary droughts), near the sea in coastal and delta areas, near a shallow saltwater table, aeolian deposits (sea spray, aerosols), endoreic zones (sebkhas, chotts). A so-called «secondary» salinization is induced by anthropogenic causes: mismanaged irrigation, old irrigation techniques, irrigation with waters rich in salts, deforestation, fertilizers containing potassium and nitrogen salts, atmospheric deposition near industrial sites. Above a given threshold of soil salinity, plant growth, crop production, water and soil quality are severely affected up leading to accelerated soil erosion and land degradation or ecosystem desertification (Gorji et al. 2015).

The soils of Mediterranean countries are particularly affected by salinization (Photo 3) because of the semi-arid to arid climate and the development of intensive irrigation for agriculture by building many storage and irrigation schemes (dams, hillside dams, canals and water distribution pipes). The consequences of climate change (increased rainfall variability and water scarcity, freshwater evaporation increase and higher plant evapotranspiration rates) will result in a concentration of soluble salts in the water bodies and the extension of soil salinization. The predicted sea level rise by the Intergovernmental Panel on Climate Change (IPCC) scenarios will impact coastal areas and wetlands (deltas of major rivers like the Danube, the Ebro, the Mejerdah, the Nile, the Po and the Rhone) and promote the saline contamination of coastal aquifers due to sea water intrusion. The overexploitation of upper fragile fresh water lenses overlaying denser brackish aquifers will intensify with the increased needs for agricultural, industrial, touristic and domestic activities which are mainly located along the coast (Kuper et al. 2009; Ashour and Al-Najar, 2012; Mansour and Hachicha, 2014).

*Photo 3*
*Irrigated pomegranate crop in the clayey and saline soils of the Kairouan alluvial plain (Central Tunisia). The drip system is placed on the ridges for optimal water supply and salt leaching. The white spots (salt efflorescence) correspond to the highest soil salinity, where the trees are dead. The inter-ridges are ploughed to promote rainwater infiltration into the soil and prevent the invasion of weeds.*
*J.-P. Montoroi.*

# Main principles of desertification control and land rehabilitation: underlying ecological conditions and processes

A cover must be kept at soil surface to prevent crusting, water and wind erosion. To reduce the risks of tillage erosion, tillage operations and tillage depth should be limited. No-till agriculture associated with permanent cover is only possible where rainfall regimes allow sufficient biomass production. No-till farming can be very effective in reducing water erosion and runoff production at the plot scale. Attention must be paid on the plot length to reduce the risk of gully erosion.

In dry Mediterranean zones (annual rainfall < 300 mm) where vegetation cover cannot be continuous in space and time, the ubiquitous crusts should not be considered as a symptom of desertification because they are essential elements of arid and semi-arid zones. They favour natural water-harvesting through runoff-runon processes (Valentin and d'Herbès, 1999; Assouline et al. 2015). A wide range of water harvesting techniques has been developed for centuries in dry Mediterranean zone to enable crop and fodder production. Many of them, for example Jessour (photo 4) in southern Tunisia or micro-catchments in Israel (Zhang et al. 2013) are still in use and should be encouraged.

*Photo 4*
*Jessour of the Dahars Range, Béni Khedache Road. Mean annual rainfall of 215 mm (period 1949-2001; Kallel, 2001), Average maximal temperature: 35.9°C (August period 1990-1996, Ouessar et al. 2006).*
*C. Bouet.*

## Considering the socioeconomic context

The abovementioned biophysical processes interact with many human decisions and constraints, including land users and policy makers. Both levels are crucial to lead to a successful control of desertification processes and soil rehabilitation. The top-down approach of terraces, check dams, deep drilling and reforestation has usually led to failures because the lack of involvement and interest of the land users. More success is expected through participatory and incentive approaches (De Graaf et al. 2013).

## Conclusions

Climate change associated with land use changes in the Mediterranean region are expected to induce a major latitudinal shift of the pedoclimatic zones, resulting not only from the changes in climatic averages, but also from the higher frequency of extreme events (rain and wind storms, drought, long dry spells, heat waves...), and higher seasonal and inter-annual variability. These changes should render the already shallow soils even more vulnerable to various degradation processes (tillage, water and wind erosion, salinization) favouring a desertification spiral. To hamper these alarming changes, adaptation and innovative policies should be based on a sound knowledge of the interacting processes and consider the successful practices of soil and water conservation developed in more arid regions, especially those which have been readily adopted by land-users.

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# Soil carbon as an indicator of Mediterranean soil quality

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## Two forms of carbon in Mediterranean soils

Soils are considered as one of the largest C pools on Earth, after the oceanic and geologic reservoirs. The soil C pool comprises two distinct components: soil organic carbon (SOC) and soil inorganic carbon (SIC), which roughly contribute 2/3 and 1/3, respectively (Batjes, 1996).

*Soil organic carbon (SOC)* represents about 50% of soil organic matter, by consequence “soil organic matter” and “soil organic carbon” are often confused and used interchangeably. Soil organic matter corresponds to all organic materials in soil, i.e. any material produced originally by living organisms (plant, animal, microorganisms) at various stages of decomposition. Soil organic matter is a

*Table 1*
*Estimated dryland carbon stocks*

| | Biotic (Gt) | Soil | | Total (Gt) | Ratio (%) |
|---|---|---|---|---|---|
| | | Organic (Gt) | Inorganic (Gt) | | |
| Hyperarid and arid | 17 | 113 | 732 | 862 | 28 |
| Semiarid and dry subhumid | 66 | 318 | 184 | 568 | 18 |
| **Dryland total** | **83** | **431** | **916** | **1 430** | **46** |
| **Global total** | **576** | **1 583** | **946** | **3 104** | |
| Global total ratio (%) | 14 | 27 | 97 | | |

Source: Millennium Ecosystem Assessment, 2005 (dryland chapter)

continuum of simple and complex molecules. It constitutes a dynamic soil carbon pool, regularly fed by organic residues and in interaction with the mineral particles of the soil. Soil organic matter influences soil functions and properties. It has a key/role in the overall behaviour of soils and agroecosystems, as it provides energy for soil microorganisms, nutrient storage and supply (nitrogen, phosphorus and potassium) for plant production, improves soil structure and is thus involved in the ability of soil to hold water and resist erosion. Maintaining organic carbon in soil is equivalent to maintaining the soil organic matter and a part of the soil fertility. By consequence soil organic carbon content is often considered to be the prime soil quality indicator, with respect to its agricultural and environmental functions.

*Soil inorganic carbon (SIC)* represents different C forms involved in a solid-solution-gas phase equilibrium, as carbonate minerals (mainly $CaCO_3$), as aqueous carbonic dioxide, bicarbonate $HCO_3^-$ and carbonate $CO_3^{2-}$ ions in soil solution, and as a gas carbonic dioxide $CO_2$. In humid regions, SIC tends to get dissolved and fluxes into the groundwater or precipitates deep in the soil or geologic system, whereas in dry regions it precipitates at relatively shallow depths as a result of sparse rainfall and insufficient leaching (Gocke et al. 2011). Because of this, about 90% of the global SIC pool is found in arid and semiarid regions (Eswaran et al. 2000), such as the Mediterranean region. Despite agreement about its large size as a carbon pool (950 Gt), little attention has been paid to the dynamic of the SIC pool, which is considered to be very slow and less influenced by anthropogenic disturbance than the SOC pool. However, there is increasing evidence that the solid-solution-gas phase equilibrium in the SIC system may be shifted in one way or another (to $CO_2$ emissions or $CaCO_3$ precipitation) by external factors such as management practices, e.g. cropping and irrigation, and human-led environmental changes.

The dynamics of the SIC pool could be impacted by land management. Indeed, irrigation to enhance crop production in the Mediterranean region is often practiced with groundwater laden with dissolved calcium bicarbonate ($Ca^{2+}$ and $HCO_3^-$). When used for irrigation, this water promotes calcium precipitation in the form of calcium carbonate and could modify the equilibrium between the different forms of inorganic carbon in soil. The addition of plant residues enhances biological activities (root and microorganism respiration) resulting in an increase in $CO_2$ partial pressure, which may either lead to an enhanced trapping of $CO_2$ through carbonate precipitation, or to a decrease in soil pH resulting in the dissolution of carbonates. There are very few studies that try to understand and explain the contradiction between the results of the impact of soil management on SIC dynamics (Monger et al. 2015). More research is needed on that specific issue.

## How soil organic carbon benefits soil fertility and the environment

In semi-arid regions, improving water management while avoiding loss of soil organic matter, and thus maintaining the soil organic carbon pool, is essential to preserve soil against degradation and ensure food security for societies. Combating soil desertification requires effective organic matter and water management in order to maintain a sufficient level of fertility for sustainable production. Thus, the techniques for water and soil conservation management are also recognized as effective soil organic carbon management techniques. Water conservation and fertile sediment retention enhances soil fertility and facilitates the growth of natural or replanted vegetation around the structures as half-moon or stone bunds.

Soil carbon is linked to soil organic matter, as 50% of soil organic matter is soil organic carbon. Soil organic matter ensures a part of soil fertility as it allows for storage of nutriments for plant growth, stimulates soil biodiversity and contributes to soil structure stability. Maintaining the soil organic matter pool is essential in sustainable land management and soil productivity (fig 1).

Besides soil fertility, soil organic matter is also seen as the biggest C reservoir of terrestrial ecosystems after carbon fossil stock (see fig 2). Storing C in soil is seen as a means to mitigate atmospheric $CO_2$ concentration and Green House Gas emissions (GHG emissions, fig. 1). Thus C balance from soil to the atmosphere is a local issue for soil conservation, agricultural production and food security and at the same time a global issue to limit climatic change. Soil carbon is recognized as an indicator of soil quality in terms of its agricultural and environmental functions.

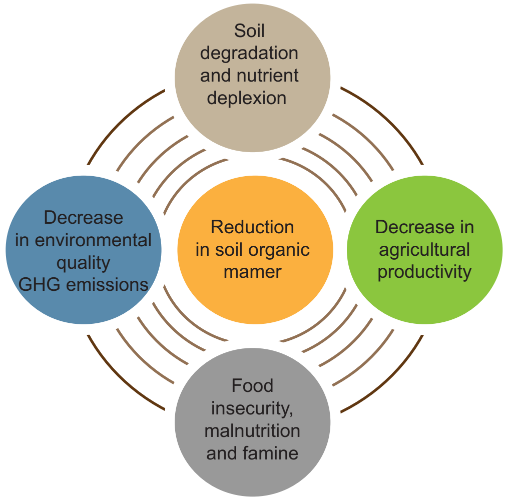


*Figure 1*
*The vicious circle between the decrease in soil organic pools, land degradation and food insecurity (from Lal, 2004 : Soil carbon sequestration impacts on global climate change and food security. Nature 304(5677): 1623-1627).*



# Measuring or evaluating SOC after changes in management practices

Most Mediterranean soils exhibit low (≤2%) or very low (≤1%) SOC content especially in the southern side of the Mediterranean sea, with a mean SOC content of about 1.1% in the top 0-30 cm for the North Africa region and national means of SOC ranging from 0.67 to 0.79% for Morocco, Tunisia, Algeria and Egypt (Henry et al. 2009). Limited SOC content in the Mediterranean soils is mainly the result of a limited net primary productivity. These low C inputs driven by limited soil moisture availability could be exacerbated by crop residue competition for livestock feeding or the introduction of long fallowing in the crop rotation. Besides low C inputs to the soil, some agricultural management, such as intensive deep-tillage (e.g. moldboard ploughing) may also boost SOC losses. Deep-tillage enhances microbial activity by homogenization of soil moisture and oxygenation and incorporation of crop residues into deep soil, and thus speeds up soil organic matter mineralization and loss. Farming practices that enhance carbon storage are needed for sustainable land management, soil productivity and protection of the environment.

Many soil and management techniques have long been known to maintain or enhance the soil organic matter content: use of compost, manure, cropping residues to “feed” the soil: soil cover techniques, grassed strip, trees, or any

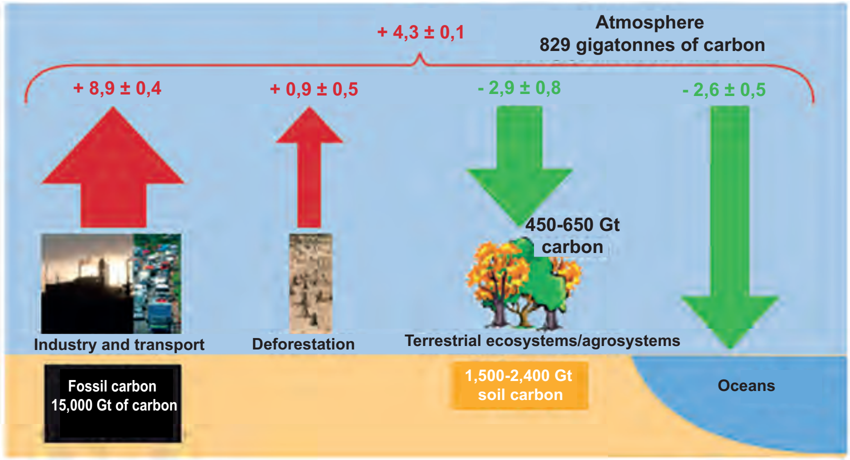


*Figure 2*
*Human activity $CO_2$ emissions against C stocks, expressed in Gt C or in billions of tonnes of C, and fluxes, expressed in Gt C $yr^{-1}$, between ecosystems and atmosphere (mean values for 2004-2013, Le Quéré et al. 2014, Earth Syst. Sci. Data Discuss., 6, 1–90, 2014).*

land management that preserves soil from erosion, improves water infiltration and enhances soil fertility. To evaluate the efficiency of these techniques to restore, maintain or enhance the soil organic carbon stock, scientists and stakeholders need to quantify soil carbon stocks.

Countries should regularly provide national inventories of greenhouse gas emissions and potential sinks of C for the agriculture and forestry sectors. This comprises national estimates of soil organic carbon (C) stocks (Box 1). These inventories require quantifying the soil carbon stocks on large territories where variability can be large. The development of new measurement techniques for C stock monitoring, that are faster and cheaper than classical techniques are needed (e.g. infrared-spectrometry). Models are also being developed to predict the impact of agriculture and forestry changes on C balances at large scale (region to country) (Box 2).

## Carbon stock within the soil profile: the importance of deep carbon

Most of soil carbon surveys focused on the first 30 centimeters of soil (0-30 cm). However, if measured only on the topsoil (0-30 cm), SOC stocks are not representative of the real stock of C stored in the soil, especially in the deep soils of the alluvial cultivated plains. The total carbon stock could be underestimated from 30 to 65 % in Tunisia (Box 1) or on a toposequence in North Algeria (Bounouara et al. 2016) or up to 80% in Cardinael et al. 2015 (Box 3).

### Box 1
### A specific study "national soil carbon stocks, a case study in Tunisia"

Assessment of carbon contents and carbon stocks in Mediterranean soils is often difficult. The first difficulty is encountered during the sampling process, due to the presence of stones in the soils. In addition to the low organic carbon content and its heterogeneous distribution, sampling representative samples could be hard. The second difficulty concerns the analysis. Most soil carbon measuring methods estimate the total soil carbon content (organic and inorganic carbon). The soil sample must be decarbonated when the analysis is focused only on organic carbon. This decarbonation procedure is difficult and expensive.

In addition, estimation of soil C stocks requires soil bulk density values to convert C content (g C $kg^{-1}$ soil) to a mass of C per unit area (tC $ha^{-1}$). However, because it is labour-intensive, costly and tedious especially in rocky soil with a high coarse-element content, direct measurement of bulk density is often lacking for soils in arid and semi-arid conditions. Using a pedotransfert equation is an easy option to predict soil bulk density using data from soil surveys, e.g. soil texture or data easier to measure in the field. These predictive functions are specific to regional conditions and need to be built especially for the Mediterranean context (Brahim et al. 2012).

Estimation of national SOC stocks could be conducted after predictive functions using different databases, e.g. soil maps or soil types. Globally the different estimations of SOC stocks for large areas gave similar results and identified the same regions with high SOC stocks. However, the local SOC variability was not precise enough and depends on the predictive function use (Brahim et al. 11). Brahim et al. (2011) organized a soil database with 238 soil profiles corresponding to 707 soil horizons. The mean and median SOC contents of top-soil were 1.17% and 0.86% respectively. The spatial variation of SOC contents are mainly explained by the climatic zones and the soil texture. The global SOC stocks in Tunisian soils are about 0.42-0.46 PgC (0-30 cm) and 1.03-1.13 PgC (0-1m) (Brahim et al. 2011).

### Box 2
### EX-Ante Carbon blance Tool (EX-ACT)

Ex-Act is a tool developed by FAO in collaboration with IRD to perform ex-ante estimates of the impact of agriculture and forestry development projects on GHG emissions and carbon sequestration in soil and biomass. This tool is especially useful to evaluate the carbon impact of agricultural policies such as land use change incitation (i.e. deforestation, forestation, forest degradation, annual/perennial crops, irrigated rice, grasslands, livestock, inputs, energy, or other investments such as road or warehouse construction). Estimation of C balance is based on IPCC default values (Tier 1), region specific coefficients (Tier 2) are therefore needed to get more accurate C balance results.

**Box 3**
**A specific study "Agroforestry in South of France"**

Agroforestry is a land use type where trees are associated with crops or pastures within the same field. In Southern France, a sub-humid Mediterranean region, a study evaluated the potential of organic carbon storage in soil and biomass under an 18 year-old agroforestry system with hybrid walnut trees at 110 trees $ha^{-1}$ + durum wheat. The accumulation rates were 0.35 t C $ha^{-1}$ $yr^{-1}$ in the first meter of soil, and 0.75 tC $ha^{-1}$ $yr^{-1}$ in the above-ground tree biomass. The stored soil organic carbon was mostly coarse organic plant residues (particulate organic matter) which may be rather labile SOC fractions. This study demonstrated the potential of alley cropping systems to store SOC under Mediterranean conditions, but suggested that the additional SOC is vulnerable to any future land use change (Cardinael et al. 2015).

Different types of land uses or soil managements affect the stocks, dynamics and forms of SOC in topsoils but their effect on deep C is still unclear. Because SOC is considered to be less dynamic in subsoils than in topsoils, SOC in subsoils were not studied a lot. However, the SOC in deep soil can contribute to SOC stocks and also be a potential source of $CO_2$. Indeed, some studies in Mediterranean regions showed that SOM could have high C and N mineralization rates even in subsoil. This surprising result was attributed to specific pedoclimatic constraints under Mediterranean soils (Rovira and Vallejo, 1997, 2002). Therefore, SOM characterization and dynamics in deep soil horizons under the Mediterranean pedoclimate was still unclear because of few available data. Its distribution in the landscape and its forms must be characterized in order to understand its dynamics.

# The vulnerability of soil carbon

Terrestrial ecosystems play a major role in regulating atmospheric $CO_2$ concentrations, as the net balance of photosynthesis and respiration corresponds to a current terrestrial sink of about 2.6 Gt C $yr^{-1}$. Soil respiration, including autotrophic respiration by roots and heterotrophic respiration by microorganisms, has been estimated to be approximately 100 GtC $yr^{-1}$ (IPCC, 2007) with the half being produced by heterotrophic respiration. Thus it is essential to estimate and predict the impact of soil management and climate change on the microbial activities involved in SOC decomposition to predict the vulnerability or sensitivity of SOC stocks to climate change, *i.e.* increasing temperature, dry-wet cycles, and extreme events. Particular attention is currently paid to the effect of climate changes on Mediterranean region, where increased temperature, decreased and more concentrated rainfall, and an increased frequency of extreme events are forecast.

Understanding soil carbon dynamics is especially critical in semi-arid regions, such as North-West Tunisia, where SOC stocks are low and agricultural productivity is already limited by climatic conditions. A study for North West Tunisian soils indicated a moderate and positive response of soil respiration to temperature; $Q_{10}$ of soil respiration was evaluated to 1.7 (Hamdi et al. 2011). $Q_{10}$ is the proportional change in respiration with a 10 °C increase in temperature. This value of $Q_{10}$ was in the current $Q_{10}$ range values given in the literature, 2.6±1.2 (Hamdi et al. 2013). It seems that these Mediterranean soils have no specific behavior when temperature increases. However, maintaining soil at high temperature up to 40°C for one month, which could be possible in Tunisian semi-arid topsoils, decreases microbial biomass and substrate availability and consequently affects the temperature sensitivity of soil respiration.

In addition, it is not yet clear how and under what conditions the large inorganic carbon pool of Mediterranean soils may be affected by changing climatic conditions. Studies of the positive or negative effects of irrigation or rain events on the contribution of carbonates to the $CO_2$ emissions from dryland soils are conflicting (Emmerich, 2003; Serrano-Ortiz et al. 2010). In addition, no study has considered the impact of soil temperature on $CO_2$ emission from calcareous soils in drylands soil, where heat waves are expected to become more frequent and extreme within the 21st Century (IPCC, 2007). A better understanding of SIC dynamics and their role in ongoing global change is particularly critical for arid and semiarid areas, where SIC is the most important C form. In addition, certain methodological issues persist which add uncertainty to the investigation of $CO_2$ fluxes from calcareous soils to the atmosphere (Chevallier et al. 2016).

## Conclusion

As the soil carbon content varies on multiannual scales, other indicators which are more sensitive to the soil organic status can be used for earlier detection of change trends. These indicators involve enzymes, microbial biomass or soil organism biodiversity. They are more sensitive to soil functioning changes but also more complicated to obtain and to use. Soil organic carbon content is thus recognized as one of the main indicators to monitor soil quality, for its agricultural and environmental functions by many national and international institutions, initiatives and partnerships (see sub-chapter 3.5.4). As soil C dynamics is poorly studied in Mediterranean context, more research is needed in order to evaluate the content and quality of soil carbon in relation to the quality of Mediterranean soils.



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# Rethinking the management of mycorrhizal soil infectivity to restore Mediterranean and tropical forest ecosystems



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## Introduction

Desertification, one of the main causes of climate change, generally results from a variety of factors, including climatic variations and human activities. Among the man-mediated degradative activities, deforestation is considered to have a major impact by causing extinction, changes to climatic condition, desertification and the displacement of local populations (Defries et al. 2007).

Forest cover is an important source of protection from soil degradation and deforestation which impacts population structure, successional patterns and species diversity, generally inducing degradations in the physico-chemical and biological soil properties (Requena et al. 2001). These changes can be recorded in microbial functional capacity (microbial metabolism, biomass and composition, enzymatic activities and soil organic matter flux) which is mainly involved in soil quality and function (Chaer et al. 2009). Many studies have also shown that deforestation and soil cultivation alter soil microbial community structure (Bossio et al. 2005) and may lead to reduction in microbial biodiversity (Chaer et al. 2009).

Among components of soil microbiota, mycorrhizal fungi are known to be essential key components of sustainable soil-plant systems, especially in arid ecosystems (Duponnois et al. 2011). The mycorrhizal symbiosis mobilizes and transports nutrients to roots (Smith & Read, 2008), reduces water stress (Augé, 2001) and improves soil aggregation in eroded soils (Caravaca et al. 2002). It has also been reported that arbuscular mycorrhizal (AM) fungi affect the diversity of plant communities (van der Heijden et al. 1998)) and influence relationships between plants (van der Heijden et al. 1998).

Since trees are a primary source of protection from soil degradation, many afforestation programs have been undertaken but with generally low performance in terms of productivity and seedling survival after outplanting (Duponnois et al. 2005a). These deficiencies have usually been recorded in Mediterranean semi-arid areas known to have low bioavailable phosphate content and high phosphate retention capacities (Duponnois et al. 2011). This environmental context represents the most favourable conditions for AMF's potential to increase plant growth without any mineral fertilizers (Rodriguez & Sanders, 2015). Unfortunately, this microbial resource has been largely neglected despite numerous studies focused on this symbiosis.

The native inoculum potential of AM fungi in arid and semi-arid Mediterranean ecosystems is generally limited which, in turn, prevents plant establishment and growth (Smith& Read 2008). It is necessary to apply mycorrhizal inoculation technologies or to manage native AM fungus communities to replace or reinforce the mycorrhizal potential in these degraded areas (Duponnois et al. 2011).

## Approaches to AM application in forestry practices

This chapter aims to describe different practical approaches to integrate the AM symbiosis in forestry practices through a "reductionist" approach (also named Controlled mycorrhization) (Inoculation of optimized AM fungal strains to improve the plant growth in unfriendly conditions) or a "holistic" approach (Suitable management of AM fungal diversity for ensuring AM fungi – dependent ecosystem services) (Rodriguez & Sanders, 2015). Each of these cultural practices will be illustrated by results from field experiments performed in Mediterranean and tropical areas.

# The "reductionist" approach (controlled mycorrhization)

In recent decades, considerable research has been made by using specific mycorrhizal fungal strains to enhance outplanting performances with forest tree species (Caravaca et al. 2002). Hence, numerous studies have reported the beneficial effects on plant growth resulting from AM fungal inoculation during the nursery plantation. Among all the AM fungal strains tested in these experiments, *Rhizophagus irregularis* has attracted great interest because of (1) its world-wide distribution, (2) its high genetic variability and variation in effects on plant growth and (3) its ability to be produced in an *in vitro* system.

Some of its impacts on the growth of different tree species in controlled conditions are reported in table 1. Most of these experiments have been performed in controlled conditions and few studies have clearly demonstrated the benefits

*Table 1*
*Impact of R. irregularis on the growth of tree species in controlled conditions after different times of cultivation*

| **Tree species** | **Time (months)** | **Impact of R. irregularis on plant growth** | | **References** |
|---|---|---|---|---|
| | | **On shoot biomass** | **On root biomass** | |
| *Acacia holosericea* | 4 | + 77.5% [(1)] | + 122.7% [(2)] | Duponnois et al. (2005b) |
| *Fraxinus uhdei* | 3 | + 250% | + 180% | Ambriz et al. (2010) |
| *Cupressus atlantica* | 3 | + 48.7% | + 155.2% | Ouahmane et al. (2007) |
| *Acacia mangium* | 3 | + 20.2% | + 50% | Weber et al. (2005) |
| *Citrus aurantium* | 5 | + 273.3% | + 66.3% | Nemec & Vu (1990) |
| *Acacia tortilis* | 4 | + 499.2% | + 78.3% | André et al. (2003) |
| *Parkia biglobosa* | 2 | +7.1% | + 25.5% | Guissou et al. (1998) |
| *Tamarindus indica* | 2 | +6.7% | + 36% | Guissou et al. (1998) |
| *Zizyphus mauritiana* | 2 | + 130.3% | + 152% | Guissou et al. (1998) |
| *Alnus cordata* | 2 | + 441% | + 1407% | Monzon & Azcon (2001) |
| *Alnus incana* | 2 | + 644% | + 1041.2% | Monzon & Azcon (2001) |
| *Alnus glutinosa* | 2 | + 996.7 % | + 1194% | Monzon & Azcon (2001) |
| *Acacia senegal* | 3 | + 171.4% | + 127.3% | Ndoye et al. (2013) |
| *Phoenix dactylifera* | 5 | + 140.4% | + 165.4% | Baslam et al. (2014) |

[(1)] (Shoot biomass of mycorrhizal plants / Shoot biomass of non mycorrhizal plants) x 100. [(2)] (Root biomass of mycorrhizal plants / Root biomass of non mycorrhizal plants) x 100.

of fungal inoculation in the field. The degree of mycorrhizal responses on a reafforestation site depends on the status of fungal colonization at planting, and the persistence of introduced fungi and other biotic and abiotic factors at the planting site (Duponnois et al. 2011).

Hence, the use of AM fungi and plants adapted to the local environmental conditions may be a prerequisite for the success of reafforestation programmes (Duponnois et al. 2005a). The potential effect of mycorrhizal inoculation with native AM fungi on the survival rates and early growth performance in the field of Mediterranean tree species (i.e. cypress, carob) has been assessed in a few studies (Manaut et al. 2015). The results showed the high potential of this approach by sustainably improving the growth and nutrient status of both tree species and also by inducing a positive soil microbial environment for nutrient cycling and environmental stress resistance (figs. 1 & 2).



## The “holistic” approach

It has been reported that certain shrubs react positively to the survival and growth of other neighboring plant species by creating a better environmental habitat with low stresses from high radiation and temperature as well as from soil nutrient and moisture deficiencies (Callaway & Walker, 1997) named “the nurse-plant syndrome” (Niering et al. 1963). The ecological facilitation between plant species results in the patchy distribution of the vegetation commonly observed in Mediterranean areas, especially in degraded ecosystems (Callaway & Walker, 1997).

Hence it has been suggested that the use of nurse plants as planting microhabitats in Mediterranean degraded ecosystems could promote the survival and development of native tree species and constitute an alternative reforestation technique compared to the standard practices (Duponnois et al. 2011). The “fertility islands” or “resource islands” (Schlesinger et al. 1996) resulting from the establishment of these nurse plants show a higher arbuscular mycorrhizal (AM) soil infectivity compared to the adjacent soil away from plant influence (Duponnois et al. 2011), which can improve plant growth and survival in arid conditions, by increasing the supply of nutrients to the plants (especially for soil P uptake) (Smith & Read, 2008), enhancing soil aggregation in eroded soils (Caravaca et al. 2002) and reducing water stress (Augé, 2001).

After three years’ plantation, it was reported that the association between *C. atlantica* and a nurse plant, *L. stoechas*, enhanced the growth of *C. atlantica* and provided better soil microbial characteristics compared to the control treatment (fig. 3) (Duponnois et al. 2011). AM mycelium network, total microbial activity, dehydrogenase activity, phosphate-solubilizing fluorescent pseudomonads and N, P nutrient uptake by *C. atlantica*, were significantly higher in the presence of *L. stoechas*. This pioneer shrub facilitated the early establishment of Cypress seedlings by improving soil microbial characteristics and AM fungus community development. Since the facilitative effect of one

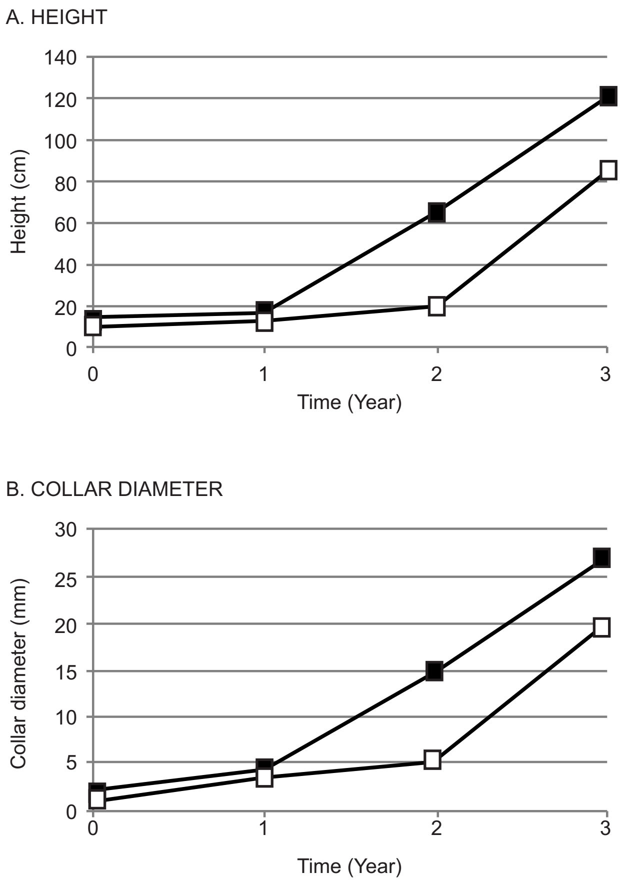


*Figure 1*
*Height and collar diameter of carob outplants in the field, either inoculated with AM fungi (■) or non-inoculated (control □). An asterisk indicates a significant (P < 0.05) difference between the two treatments for a given year (From Manaut et al. 2015).*

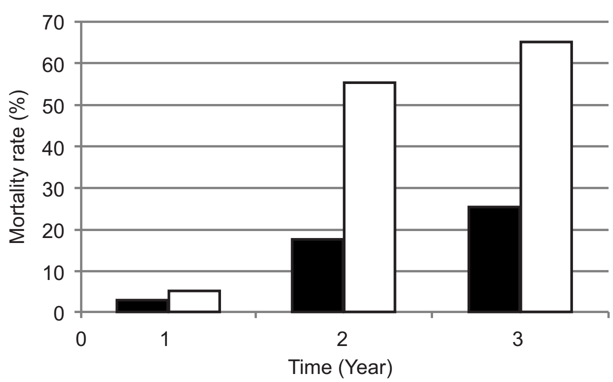


*Figure 2*
*Cumulative mortality of carob outplants in the field, either inoculated with AM fungi (■) or non-inoculated (control □) during the three years of plantation (From Manaut et al. 2015).*

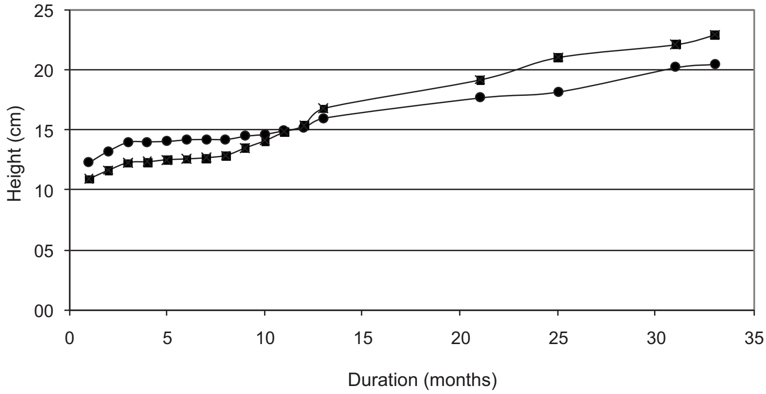


*Figure 3*

*Time course changes in plant height (expressed in cm) of* C. atlantica *outplants growing under natural conditions in the High Atlas Mountains (Morocco), either non-inoculated (Control) (●) or associated with* L. stoechas *plants (■). Symbols represent means (± standard error of the mean). An asterisk indicates that the difference between the height of uninoculated* C. atlantica *and* C. atlantica *associated with* L. stoechas *is significant in the corresponding month according to the Newman Keul's test ($p < 0.05$).*

plant species on another increases with abiotic stress (Callaway, 1995), the benefits of this technique would be useful in reforestation programs undertaken to rehabilitate degraded areas in the Mediterranean region (Duponnois et al. 2011). Other shrub species have been identified for their potential nursing effects on Mediterranean tree species (fig. 4).

## Conclusion

These data show that the management of the mycorrhizal soil infectivity through different cultural approaches (reductionist or holistic approaches) has large potentialities to improve the performances of afforestation programmes, especially in Mediterranean and Tropical areas. This biological tool must be used according to the biological characteristics of the targeted areas (physic-chemical characteristics, biological characteristics) in order to reach sustainable objectives in forest ecosystem productivity and resistance. Hence ecological approaches at community and population scalesmust be encouraged with a view to better informed management of AM fungi in order to propose practical solutions to manage forest ecosystems in a sustainable manner.

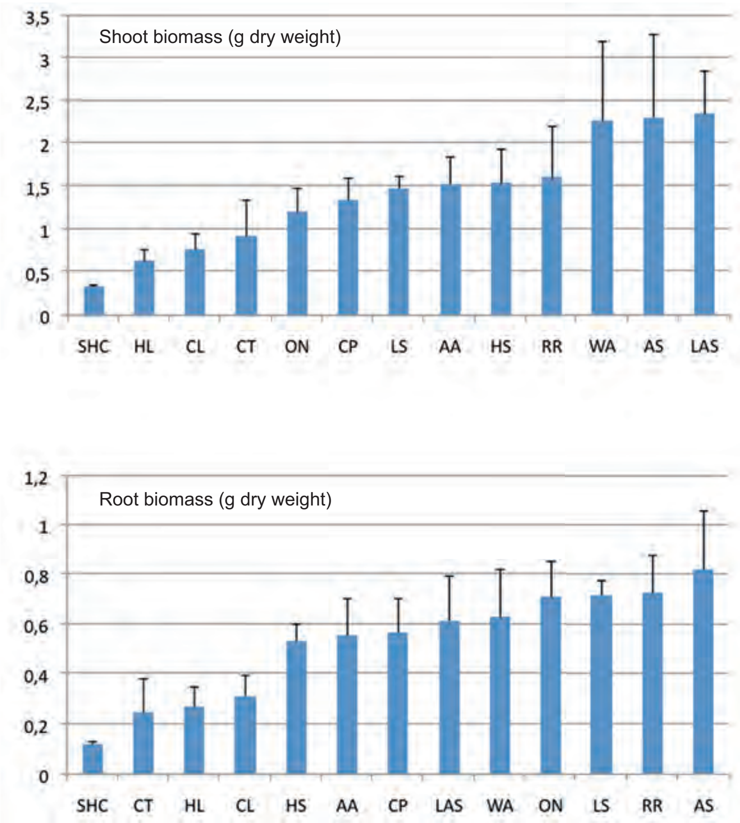


*Figure 4*

*Growth responses of* Acacia raddiana *seedlings to the soil origins collected under shrub species native from Morrocan arid areas after 4 months' culture in glasshouse conditions (Unpublished data). HL:* Helianthemum lupii*; ON:* Ononis natrix*; HS:* Haloxylon scoparium*; RR:* Retama retama*; WA:* Withania adpressa*; LS:* Lavandula *sp.: LAS:* Launea *sp.; CL:* Cleome *sp.; CT:* Convolvulus trabutianus*; AA:* Artemisia herba alba*; AS:* Astericus *sp.; SHC: Soil non influenced by plants.*

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Chapter 6

# Adapting to global change in the Mediterranean Sea*

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## Abstract

The Mediterranean is one of the world's most remarkable regional seas, with a high level of activity in several sectors: fishing, mining, industry, town expansion, trade and tourism. However, the opportunities are currently outweighed by the threats, particularly in terms of marine and coastal resources. Nevertheless, the increasing knowledge and awareness amid the region's societies and States of the risk of negative impacts related to unpredictable changes lie behind an ever greater determination to understand the various phenomena involved and to make choices conducive to more positive change. Moreover, Mediterranean ecosystems seem to provide increasing opportunities for various forms of "Blue Growth" – as long as resources are considered as a legacy rather than a mine to be endlessly exploited: the management of resource flows should gradually take precedence over the exploitation of stocks. But for this to become a reality, comprehensive and relevant data sets, methods and objectives are needed in all disciplines, from physics to governance. Meanwhile, the social aspects of the issue are emerging in a variety of ways, via new demands from a public that is increasingly aware of food security, health, sustainability and ethics. There is therefore an urgent need for greater cooperation among all actors, coupled with an ability to outline the long-term

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choices in a context of uncertainty and increasing risk. In marine sciences – including social studies, research must draw on shared and open methods to (i) help facilitate the debates between all stakeholders; (ii) contribute to the collective selection of measures that will not later be regretted and (iii) promote a sense of ownership among all parties of the actions necessary in the Mediterranean. As with the climate change issues, research in the Mediterranean must contribute to avoiding the unbearable while managing the inevitable, at least as far as possible within this iconic maritime region.



## Résumé

De toutes les mers régionales du globe, la mer Méditerranée est l'une des plus singulières. Elle concentre une intense activité extractive, industrielle, commerciale, urbaine et touristique, ce qui représente plus de menaces que d'opportunités, notamment pour ce qui concerne les ressources marines et côtières. Mais le progrès des connaissances sur cet espace et la prise de conscience par les sociétés et les Etats riverains des risques de changements non maîtrisés à forts impacts négatifs conduisent à une volonté croissante de compréhension des phénomènes en cours et de choix raisonnés de meilleurs scénarios d'évolution. De plus, ces espaces apparaissent de plus en plus comme des chances de croissance dite « bleue » mais sous réserve d'une approche plus patrimoniale que minière de valorisation des ressources. Désormais, la gestion des flux devrait prendre peu à peu le pas sur l'exploitation des stocks sous réserve de disposer d'ensembles structurés de données, de méthodes et d'objectifs dans tous les compartiments de ce vaste écosystème, de la physique à la gouvernance. Enfin, les dimensions sociétales émergent de manière multiforme via des demandes nouvelles d'un public mieux informé et soucieux de sécurité alimentaire, de santé, de sûreté, de durabilité et d'éthique. Dans ce contexte s'impose peu à peu le besoin récurent d'une concertation de tous les acteurs et d'une capacité d'éclairer les choix de long terme dans un contexte d'incertitudes et de risques accrus. Dans tous les domaines des sciences marines, dont les sciences sociales, la recherche, par l'usage de méthodes partagées et transparentes, peut et doit contribuer (i) à faciliter les débats entre porteurs d'enjeux, (ii) à la sélection collective des mesures inévitables à court comme à long terme, et enfin (iii) à l'appropriation par toutes les parties des actions nécessaires à mener en Méditerranée. A l'instar du changement climatique, il s'agit bien pour la recherche en Méditerranée de contribuer à éviter l'ingérable et de gérer l'inévitable au moins aux dimensions de cette mer régionale emblématique.

# The Mediterranean: key facts and figures

The Mediterranean is a virtually closed sea, covering about 2.5 million km² between the African and Eurasian plate boundaries, and is the focus of intense geologic activity, notably seismic and volcanic. From a physical perspective, it is broadly split into two well-defined basins (Western/Eastern) which are subdivided into numerous contrasting entities. Major rivers generate rapid horizontal and vertical transfers that are strongly influenced by weather and climate conditions and subject to wide variations on all time scales.

Biologically speaking, this sea is one of the "hot spots" of marine biodiversity. It shelters a great number of species, with a high ratio of endemic species, Coastal lagoons, salt marshes, estuaries, deltas, rocky and sandy coastlines, sea grass and coralligenous beds, canyons, plateaux, undersea mountains are all remarkable habitats that favor the diversity of organisms (Benoit and Comeau, 2006).

From a geopolitical standpoint, this sea has represented a hub for trade and culture between the peoples of the region since ancient times. Today, it constitutes a shared space for 23 countries and is both traversed and exploited by these countries as well as third parties. It is also a disputed space, with tensions between users and competition for resources. Nevertheless, for most maritime-related issues, neighboring countries are bound by a 'common destiny'. They therefore need to cooperate in terms of resource assessment, observation, monitoring and controls as well as management of marine resources (Lejeusne et al. 2010; Mermex group, 2011; Sénat, 2012; Marine Board, 2013).

In human terms, in 2011, the neighboring countries accounted for 475 million people, a third of whom lived on the coast, with a significant proportion in "megacities". From the shore to the open sea, the Mediterranean Sea is the focus of numerous activities: navigation, exploitation of living and mineral resources and tourism (UNWTO, 2011). It also provides a wide range of ecosystem services upon which the quality of life of coastal communities and certain economic activities depends (Plan Bleu, 2008; Herr and Galland, 2009; Rochette et al. 2012).

There has been an increase in the intensity and frequency of climate change-related disturbances (sea-level rise, increasing water temperature and acidification, coastal erosion...), as well as societal changes, including over-fishing, rising recreational uses, chemical pollution and biological invasions, etc. As a result, marine ecosystem services are affected and will increasingly be so in the future.

In terms of a forward-looking vision (2030-2050), research, innovation and training have a vital part to play in providing the necessary knowledge to cope with and guide these changes towards a desirable future (Rossetti, 2011; EC, 2011; Lionello 2012). This cannot be envisaged without tackling the issues and giving consideration to the Mediterranean basin as a whole (Ecorys, 2012; Seas-era, 2012).

To this end, the French National Research Agency (ANR) supported a study and workshop on the future of the Mediterranean Sea in response to global changes (ARP MERMED). Its purpose was to define priority areas for research, in order to help build the capacity of Mediterranean societies, in terms of anticipation and adaptive management. Managed by Agropolis International, ARP MERMED coordinated 47 French and international institutions working together from April 2013 until September 2014 and involved 130 experts from 10 countries: France, Italy, Spain, Greece, Algeria, Morocco, Tunisia, Egypt, Turkey and Belgium. A final report and 100 foresight studies factsheets are available online: www.agropolis.org/arp-mermed

# Characterizing, assessing and preventing marine environment-related risks for Mediterranean societies

The Mediterranean coasts are exposed to multiple complex and interlinked risks. Natural hazards, whether geological or hydro-meteorological, result in coastal zone submersion and erosion risks. The effects of climatic and societal changes on the marine environment and organisms entail risks for human health and for the sustainability of ecosystem services on which coastal societies depend. The concentration of population and activities on the coast together with the increasingly artificial nature of coastlines and higher sea-levels, contributes to the greater vulnerability of coastal societies.

## Submersion and erosion risks in coastal zones

The Mediterranean Basin is located on the Africa-Eurasia convergence zone and is tectonically very active, notably in the Eastern Mediterranean. Seismicity is more diffuse in the Western basin and spread out over many faults, about which very little is known. Submarine avalanches or volcanic eruptions also occur in these situations. These telluric events can provoke devastating tsunamis. Hydro-meteorological hazards are also the cause of current and future marine submersion risks. Atmospheric depressions generate a temporary rise in sea level which, combined with overtopping linked to wind and waves, is often accentuated by relatively steep inshore slopes. Flash floods – sometimes combined with storms at sea – also impact on flooding in the coastal plain.

Combined with these hazards, sedimentological phenomena – sometimes altered by human activities – play an important part in the evolution of coastal erosion. But they are still poorly understood, due to difficulties in obtaining in situ measurements of sediment flows on different spatial and temporal scales. This sea is particularly sensitive not only to deep sea basin sediment transfers but also to the mechanical alteration of rocky coasts and beach erosion.

Climate change will bring about a rise in sea level and alter the hydrological regime and storm patterns, with an influence on coastal hazards. On low level coasts, this will result in a gradual loss of coastal land, erosion of the coastal strip and temporary submersion linked to storms. In addition, there will be a higher frequency of river floods. The extent of territories exposed will thus increase considerably in the coming decades. Saltwater intrusions inland, contaminating fresh water drillings in coastal aquifers have also been observed. This issue is crucial for many countries, notably on the southern rim. Consequently, research should help improve the prediction and prevention of submersion risks and coastal zone erosion in the Mediterranean, and the related vulnerability of populations.

## Sources, flows, fate and impacts of pollutants

Human activities are the source of a great deal of waste, pollutants and disturbance. Pollution originating from atmospheric emissions, discharges into the sea and the recreational sector, is a factor to varying degrees. Maritime traffic transiting through this sea (30% of global flows) is an additional source of pollution, both chronic and accidental, while aquaculture sometimes leads to local concentrations of organic matter. Pollutants initially affect the coastal environment, then offshore areas and accumulate in secondary reservoirs. These pollutants contaminate water and living organisms. They affect the balance of marine ecosystems and threaten certain activities and uses. Specific forms of oceanic circulation in this sea make the residence time of deep water very short, resulting in particularly rapid impacts. High concentrations of certain toxic elements such as mercury and PCB, found in the top predators consumed by man, leads to significant human health risks. Knowledge requirements focus in particular on inputs (notably new pollutants), flows (and floods), the fate of contaminants, notably in the trophic chain, and technical solutions for remediation.

## New species

The growth of human activities and the effects of climate change have also altered the composition and distribution of certain species in the Basin. This includes the introduction of new species, changes to the distribution areas of some species or their proliferation with changing environmental conditions. As a result, biodiversity is constantly changing due to the passive arrival of new species from the Atlantic and from the Red Sea. Global changes also have an impact on the parameters of seawater, which has consequences for species development and distribution. Certain effects can also be observed in bacterial populations such as the change of host, proliferation within the ecosystem and new virulence factors, which could explain the emergence of pathogenic micro-organisms. These changes represent risks for marine ecosystems and humans such as the loss of biodiversity, the impact on services provided and human toxicity. Research needs to focus on the study of the pathways, vectors and impacts concerning new species in this sea and solutions for their control.

# Conducting research in support of sustainable activities

The interaction between changing environmental conditions, ecosystem services and their sustainable use is a relatively new phenomenon, which requires innovative research. This research should concern not only traditional activities (such as artisanal fisheries) but also fast-developing activities such as aquaculture, marine biotechnology, eco-design and ecological engineering geared to reducing the impact of human exploitation or restoring the environment.

## Small-scale fisheries

Most fishing in this sea is artisanal: specialized flotillas supplying an inter-regional market and opportunistic flotillas, meeting localized, scaled-down and changeable demand. Both require significant technical and financial resources. The scarcity of deep water resources combined with the limited continental shelf area and the low productivity of the sea have restricted potential expansion. Today, the fishing industries are in crisis. The definition of standards for the sustainable development of fishing activities and the management of their impacts requires greater consideration of the biological, historic and human data that are key to their maintenance, adaptation and diversification.

## Sustainable aquaculture

Aquaculture has become a major industry in the Mediterranean, with the pioneering development of shellfish farming, followed by marine fish farming. Today, aquaculture production has exceeded fisheries catch and its growth should continue at a steady pace for the next decade. This rapid growth can be the source of conflicts of use and pollution phenomena, the salinization of low-lying land and biodiversity loss, etc. Developing sustainable aquaculture is based on adopting an ecosystem approach that seeks to optimize the supply of commercial services while ensuring the long-term future of production process (water quality, seed production, etc.). Research must therefore focus on farmed organisms (notably genetics), production systems (reduced impact on environment), microbiological engineering to enhance plant-based food digestibility, new foodstuffs and the governance of the industry, including foresight analysis.

### "Blue biotechnologies" of the future

Technological progress has given us increasing access to knowledge of the marine environment and opened the way to discovering and exploiting new biological marine resources. These can be the target – or source – of a range of biotechnological applications, with proven or potential economic interest (for food, energy, materials, molecules, processes, etc.). In particular, unicellular phototrophic organisms present high photosynthetic yields and great metabolic plasticity without requiring arable land or fresh water. Marine micro-organisms are a source of secondary metabolites and specific bioactive compounds. The development of "omics" technology provides unprecedented access to an exploration of Mediterranean microbial biodiversity.

### Eco-design for maritime activities and ecological engineering

Regulatory and technological innovations will be required to reduce the impacts of human activities in this sea, notably restoring degraded habitats. Ecological engineering and eco-design are emerging sectors in the coastal environment. The global aim is to harness environmental processes in a way that favors society and is compatible with maintaining ecological balances, by combining design, study, monitoring and project management. The field of research is broad, from the enhancement of natural ecosystemic functions to the design of sustainable coastal constructions with multiple uses, such as marinas or offshore wind parks.

## Defining scales for structuring and managing resources and uses to improve their governance

The management measures of the main maritime activities in the Mediterranean are often delineated in space because of governance rules. A key factor in their effectiveness is their coherence in terms of space and time, at the relevant scale of the targeted ecosystem. This requires the structuring of functional scales of resources, uses and governance to make current management measures more effective.

## Relevant spatial-temporal scales

The functions ensured by an ecosystem community of organisms are necessary to maintain the ecosystem itself but can also be exploited by humans. The management framework that is put in place can therefore address various objectives in connection with the conservation of ecosystems and biodiversity and maintaining productive functions exploited by humans. This dynamic balance for sustainable exploitation requires more research into the components of all marine ecosystems, from habitat to climate change and species connectivity.

## Relevant scales of organization and governance

The four main instruments of governance in this sea are the Barcelona Convention, the General Fisheries Commission for the Mediterranean (GFCM; FAO subsidiary), the ACCOBAMS (Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea) and the CIESM (Mediterranean Science Commission). All are linked by memoranda of cooperation enabling improved institutional connectivity and thus greater effectiveness. At a European sub-regional level, Europe exerts considerable influence on national and regional institutions to standardize structures and regulations. Numerous tools are supported by the various institutions: ecosystem approach (EcAp), integrated coastal zone management (ICZM), marine spatial planning, protection (e.g. Natura 2000 at Sea, Marine Protected Areas), etc. Better governance requires better knowledge of instruments, administrations and management methods currently in place, taking into account the intensity of human activities and the risks of cumulative impacts.

## Current management measures

Any strategy to improve management measures must be initially based on assessing the effectiveness of current measures in relation to targets. However, these assessments are relatively rare and difficult to implement. Besides, the need for a more operational application for the entire basin involves consultation, collaboration and cooperation between neighboring countries and consultation and dialogue between stakeholders. The proposed measures must rely on existing systems. This includes the European Marine Strategy Framework Directive, the Mediterranean Action Plan (as part of the Barcelona Convention) and the GFCM. Furthermore, there are several types of governance at global level following a gradient between two extremes: from “bottom-up” management (through local professional associations: Prud’homies, Cofradías...) to “top-down” management (through federal control and policing). More applied research is needed notably in developing a “maritime” method to assess ecological functions using a standard approach for indicators, metrics and reference points, in formulating laws and regulations according to the “polluter pays” principle) and to limit the introduction of exotic species.

# Understanding the integrated operation of the "Mediterranean Sea dynamic system"

Despite recent progress, the scientific community still faces many challenges in terms of the physical, chemical, biological and biogeochemical dynamics in the Mediterranean Sea and their interactions. Given the rapid climatic and societal changes in the Mediterranean, it is crucial to understand the processes at work in order to be able to reduce the human footprint on the marine environment.

## Physical dynamics

The way the Mediterranean Basin functions physically is influenced by highly contrasting physiography in terms of coastal continental land masses, the shoreline, continental shelves and deep basins and their connections. In addition, this sea is submitted to a complex and still largely unpredictable hydro-meteorological process. These two factors interact with hydrodynamics and various types of transfers, particularly sediments. Numerous scientific challenges must be met if we are to better understand how the Mediterranean marine environment functions physically, both in its different constituent parts and in their interactions on different spatial and temporal scales.

## Biodiversity

The taxonomic inventory of species recorded in this sea provides an estimate of 17,000 species. However, other facets of this biodiversity have also been explored recently through the phylogenetic and functional characteristics of certain organisms such as fish, which do not systematically appear spatially congruent with this taxonomic diversity. These observations not only raise fundamental questions but also have practical consequences for the management and protection of different biodiversity facets. There is a need for better understanding of the divergences and convergences of various biodiversity facets (taxonomic, phylogenetic, functional) with anthropic pressures at different scales. Spatial heterogeneity, temporal variability and interactions between organisms and ecosystem functions must be better understood.

## Eco-regionalisation

The limited spatial scale of the Mediterranean Sea, coupled with its strong geological, climatic and meteorological structure on a meso-scale, makes it a particularly relevant study area to define homogenous eco-regions in which conditions and assemblages can be characterized and predicted. Eco-regionalization is based on the availability of data to characterize the physical environment and describe the distribution of species as well as inferential statistical tools. Ecoregions are quite well identified on the northern shore. More collaborations are needed with the Southern region.

### Integrated models

This sea constitutes a highly emblematic, relevant study system, involving many of the world's key issues. It combines oligotrophic ecosystems, more productive coastal ecosystems, with significant socio-economic challenges (subaquatic landslip, algal blooms, etc) up to lagoons subjected to eutrophication and major environmental and socioeconomic crises (pollution, shellfish pathology, anoxy, etc). It is also characterized by large-scale thermohaline circulation, thus making it a "reduced-scale model of the global ocean".

Global changes are affecting the circulation of water and the physiology, biology, distribution and ecology of species. Indeed, global warming could lead to a drastic weakening in circulation with significant consequences for ecosystems. Finally, change scenarios vary widely. Their study requires long-term series and a capacity for simulation which opens up new challenges for current observation systems and models



## Monitoring changes and developing foresight modeling and analysis capabilities

Maintaining ecosystem services provided by the Mediterranean Sea appears vital for the food security, economic growth and well-being of neighboring populations. Environmental and social changes are particularly rapid in this sea, making it essential to have the adequate monitoring and follow-up tools and to build prospective analytical capacity, in order to better understand the vulnerability of coastal societies and services provided by the sea. These tools will help anticipate the future of these services while promoting the ability of societies to adapt north and south.

### Data, indicators and networks

A great deal of data is collected at sea by various types of stakeholders in widely different settings. Whether related to society and the economy, or the physical and biological environment, they remain scarce and not always accessible, compatible or interoperable. The lack of systematic in situ observation in the south of the basin compromises the monitoring of important parameters required to understand how the whole basin functions in general as well as tracking changes. Better organization and networking of observatory stations, scientific ships and research institutes for all required tasks, such as collecting, technology standardization, data sharing, interoperability and processing would all greatly benefit scientific knowledge and help guide decision makers.

## Understanding the past state of the Mediterranean Sea to anticipate its future

One of the current challenges for research is to develop models based on predictions for climate change and economic scenarios that make it possible to assess impacts on a regional scale. One of the ways of addressing these issues is to undertake a coordinated cross-comparative exercise of impact-models at different spatial and temporal scales for different types of models, involving northern and southern shores. Another challenge consists of describing the past state of the sea in order to understand its variability and reconstitute its evolution. This challenge can be met by re-analyzing old data with current models.

## Building scenarios to explore the future of resources and uses

The scientific community must have a long-term scientific strategy to boost its ability to provide expertise tailored to the marine resources ecosystem approach. Indeed, knowledge of marine environmental services is fragmented and lacks integration. The vulnerability of the main services provided by this sea to future environmental changes is currently unknown and its economic impact has not been calculated. It therefore seems necessary to have performance indicators on the state of environmental services in order to establish a future ecosystem management process of activities. These tools needed a collaborative and multi-disciplinary approach combining ecology, sociology, economy and governance, based on knowledge of ecosystem processes and their uses, including the development of normative medium-term scenarios through foresight analysis.

## Coastal societies and adaptation to global changes

Finally, it is worth considering the abilities of coastal societies to deal with systemic and multi-dimensional risks linked to the impacts of global changes which lie ahead. Such analyses must include the territorial changes from both a socio-economic standpoint (notably land use and demography) and a geographical one, including contrasts between countries. They will be based on an assessment of adaptation measures introduced in the Mediterranean at various levels as well as on how these strategies connect. They will also give consideration to the threshold effects (economic, social, environmental, etc.) to which adaptation will be difficult or expensive.

## Box 1
## Coastal management and climate change in the Gulf of Izmir

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### Introduction

Izmir Gulf (Bay) is one of the largest and most enclosed bays on the Aegean Sea. At its head lies the Metropolitan City of Izmir, the third largest city in Turkey. The Izmir Metropolitan Municipality covered 88,000 ha with a population of 4,168,000 in 2015. To the north of Izmir Gulf, the goverment has publicly committed itself to establishing "Species Protection and Management Areas" for the monk seal *Monachus monachus* (Guclusoy and Savas, 2003). The Gediz Delta, which is a "Cultural and Natural Asset" and a Wildlife Protection Area, is an extensive wetland including 3 lagoons and the most important bird area of the region. This gives it the status of a wetland of international importance under the Ramsar Convention of 1998. Rapid urban development connected with industry, tourism, recreation, marine transportation, fisheries and aquaculture as taken place in the coastal zones of Turkey over the last four decades. The total urbanized area includes extensive industrial zones and one of the biggest exporting harbours in Turkey as shown on the map of the bay on figure 1 (Yucel-Gier, 2010). The region's nations share a common purpose to strive for the optimal and sustainable use of coastal resources. Coastal management in Izmir Bay is an important issue due to increasing developmental pressure on the coastal zone. Whereas climate change is a crucial subject to project plans for reduction of negative impact for planning coastal zone management.

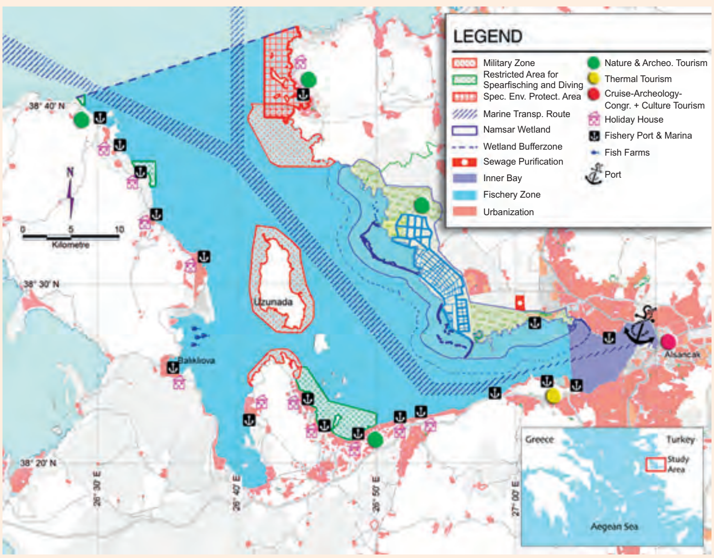


*Figure 1*
*Adaptation of Izmir Bay Land/Sea Use Plan (Yücel-Gier, 2010).*

### Issues related to Climate Change

In coastal and estuarine areas such as the Gulf of Izmir, floods are caused by sea level rise due to strong winds blowing from the appropriate direction and an abrupt drop in air pressure and the associated precipitation. This flooding is usually observed as a rapid rise in sea level followed by heavy rains. In order to understand the mechanism behind the flooding and take measures against damage, the Meteorological and Oceanographic Observation System (IZGOOS) in the Gulf of Izmir was established through the joint efforts of the Municipality of Izmir, the General Directorate of İZSU and Dokuz Eylul University (DEU), Institute of Marine Science and Technology (IMST) in 2012. Indeed, climate change does not create a new and unknown hazard by means of floods, but it probably contributes to increasing the incidence of flooding and/or affected areas. Understanding the reasons behind the events currently seen and taken action against them will therefore undoubtedly contribute to climate change adaptation (Beşiktepe, 2014)

Besides the decrease in production in lagoons at Gediz Delta, physical threats have started to cause serious issues notably in the instability of the Homa lagoon coastline in Gediz Delta. This coastline parallel to the sea is a natural barrier which separates lagoon and sea ecosystem. A 2,500 m long coastline had been harshly damaged by Southwestern storms. In order to save this lagoon, the municipality of Izmir rebuilt the lido in 2012. This kind of storm also damages the aquaculture cage farms and the expected higher frequency of occurring requires specific adaptations. *Posidonia oceanica* (L.) is one of the key species for the sustainability of biodiversity in the Mediterranean sea and notably in the bay of Izmir. *Posidonia* meadows are very sensitive to environmental changes related to human activities (town expansion, pollutants, turbidity, anchoring, aquaculture, industrial fisheries etc.). In addition, *P. oceanica* is a vital species which can be addressed as a bio-indicator for climate change (Pergent *et al.*, 2012). Therefore, the DEU-IMST has been working on the detail mapping of *P. oceanica* in order to give relevant data to decision-makers for protection regulation in Izmir bay (DEU-IMST, 2014-2016).

### Conclusion

Recent studies show that the areas most vulnerable to climate change are primarily agricultural areas (especially deltas), wetlands and touristic areas with low altitude in Turkey (Görgün & Ba¸sak, 2014). Reinforced scientific efforts and regional/local actions for monitoring, understanding, analysing risk and reducing the impacts of climate variability are essential for securing the people's well-being, the development of regional economic activities and finally the sustainability of a remarkable and symbolic area of the Mediterranean Sea.

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# Conclusion

## The Mediterranean Basin, climate change and our common future Engaging future research efforts to support policy

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Taken together, the chapters of this book constitute a rich fount of knowledge, drawing on the work of a large number of experts on climate change and its impacts in the Mediterranean basin. The observations and analyses contained in these pages prove once again that this region is a genuine hive of diversity, both in terms of its natural environment and the living conditions of the societies that surround it. It is therefore no surprise that the adaptive capacities and ability to mitigate climate change are also highly variable both between and within countries. Yet the Mediterranean countries are strongly linked by a common sea, which has always favored the exchanges of people and ideas, so the slogan 'our common future under climatic change' rings particularly true.

Over several millennia, human societies and their natural environment have co-evolved in the Mediterranean Basin. Paleoclimatological studies demonstrate that the Holocene witnessed regular abrupt climatic changes leading to important droughts, which probably played a significant role in the cultural evolution of Mediterranean societies. Even if the last millennium started with a warm period (Medieval Climate Anomaly) considered relatively similar to the recent warming, the megadroughts of the past decades are probably without precedent. Recent warming has proceeded faster than global averages, especially for summer temperatures. There is also a general increase in extreme conditions for temperature and precipitation and these trends will likely accelerate in the future. But the detailed spatial distribution of these changes remains uncertain. The warming of the Mediterranean Sea is well documented but the future of its circulation patterns is still a matter for debate.

Direct risks to people and infrastructure in the Mediterranean are linked to the water cycle and notably to hydrometeorological extremes, such as heavy rainfall leading to flash floods, but also the large swells and storm surges. Heat waves and droughts reduce crop productivity in some years and also enhance the risk of forest fire. By their nature, these extremes are difficult to study with respect to temporal trends, but knowledge has advanced substantially in recent years thanks to the development of databases and dedicated research programs.

Climate change interacts with air and water pollution and other human pressures (urbanization, agricultural intensification, expanding industry and transportation). Throughout the Mediterranean Basin, air quality continues to deteriorate. The detrimental effects of air pollution on human health are known, but better observations are needed in many regions. Although Mediterranean countries have always been highly exposed to dust storms and wildfires, their specific effects have been insufficiently studied.

The Mediterranean Sea is a major reservoir of marine biodiversity. Millions of people directly or indirectly depend on the ecosystem services it provides, in particular the provisioning of fisheries resources. Although uncertainties remain with regard to the magnitude of expected ecological changes, projections based on IPCC scenarios all confirm that climate change, through warming and acidification, is a serious threat for the biodiversity and sustainable exploitation of fishing resources in the Mediterranean Sea. The terrestrial biodiversity is also exceptional, especially in the forests, on the numerous islands and along the entire coastal zone. Risks to the functioning of these ecosystems originate do not from climate change alone but also from the destruction and unsustainable use of the landscape.

Along the coasts, the major challenge is related to sea level rise and the induced risks related to flooding and shoreline retreat, which increase substantially above 2°C warming. Many human, cultural, industrial and environmental assets are concentrated near the coasts. A comprehensive risk study has shown that the most vulnerable shores are in the poorest and less developed countries, which depend on significant economic and technological transfer from the most developed regions.

Freshwater resources are naturally sparse in much of the region. While warming, increased evaporation and decreased precipitation create additional shortages, stability of soils may also be affected by erosion due to increased flash floods. The problems are linked and intensified by unsustainable groundwater extraction and the intensification of agriculture. The highly variable climate of the Mediterranean region has enabled the development of a rich range of agricultural practices. This diversity might, if conserved, provide solutions for adaptation in the future. The Mediterranean diet is famous for its nutritional value and health advantages. Projections reveal important risks for food production in parts of the basin. Despite the fact that agriculture originated in the Fertile Crescent, modern farmers are not necessarily able to sustain long and intense droughts, especially if social and economic conditions cause additional stress, as illustrated by the 1998-2010 drought in Syria. It is currently unclear to which degree Mediterranean soils can be managed more sustainably in order to revert decades of degradation. However such strategies would not only enhance food security but also mitigate carbon losses.

Few quantitative research studies have explored the health impacts of climate change in the Mediterranean, and where available, they have been geographically limited to some specific areas within the basin. The connection between warming, new vectors, air pollution and other factors requires a new strongly interdisciplinary approach that integrates medicine, toxicology, natural and social science and engineering.

Given the multiple existing natural hazards, some of which may be enhanced by climate change, risk prevention is an acute issue throughout the region. Important progress has been made in weather and flood observation and forecasting methods. Improved communication of the population and rescue services is important for efficient adaptation measures. While catastrophic events cannot be fully avoided, improved warning systems can significantly limit their consequences.

The Mediterranean is a border and a crossing point between several highly contrasting regions in both economic and social terms – a situation which currently induces a migration influx from south to north, associated with immense human suffering and the loss of many lives. Among the multiple social and economic driving forces for this migration, climate change also plays a role that researchers are only beginning to understand.

Most contributions to this book illustrate clearly that climate change cannot be understood without deeper consideration of the human-environment co-evolution. This is true in most parts of the world but it appears that in the Mediterranean region, the problem of interdisciplinary assessment of change must reach a higher level of complexity, due to the age and intensity of the human imprint. There are indications that, given the multiple changes and large disparities, it may not have been fully realized how important the social issue of climate change is for future generations in the Mediterranean region. Climatic change affects not only nature, but also the entire economic, political and social fabric of Mediterranean society.

Action to reduce greenhouse gas emissions and enhance adaptive capacity will have to be borne by all countries and all social actors in them, in close international cooperation. Despite a great wealth of knowledge and observations, notably in the north, there is currently no state-of-the-art assessment of basin-wide risks and adaptive potential. Such an assessment would include the outcomes of regionalized modelling activities of emissions, climate and impacts, but it should also consider local knowledge and specific experience with adaptation to climate variability in the region. Most importantly, it would have to be built on a comprehensive north-south and east-west partnership in the Mediterranean basin.

Such a bridge between scientists and society is the aim of the Mediterranean group of Experts on Climatic change (MedECC) which aims:

1) To bring together the scientific community working on climate change in the whole Mediterranean basin. This includes building a bridge between existing research structures and programs and facilitating data-sharing through existing or new fora and platforms.

2) To update and consolidate the best scientific knowledge about climate and environmental changes in the Mediterranean basin and render it accessible to policy-makers, key stakeholders and citizens.

3) To contribute to future assessments of international bodies (IPCC, IPBES and others) in the Mediterranean basin.

4) To bridge the gap between research and decision-making, contributing to the improvement of policies at national, regional, and local level by providing consolidated scientific assessments on particular issues and by responding to requests by decision-makers.

5) To identify possible gaps in the current research on climate change and its impacts in the Mediterranean and interact with funding agencies for the development of new research programs to fill these gaps.

6) To help build the capacity of scientists from all Mediterranean Countries, encouraging training, research and development through collaboration.

As a regional network, MedECC expects to have enhanced abilities to produce comprehensive "state of the art" reports about climate and environmental change for the entire Mediterranean basin, which also include local knowledge from different languages and "grey literature". Based on such assessments, national and international research efforts, such as the French MISTRALS program which has inspired a part of the work reported in this book, will hopefully enhance integrated research on environmental changes in the Mediterranean Basin.

# Conclusion

## Le bassin méditerranéen, le changement climatique et notre avenir commun Lancer de nouvelles initiatives de recherche pour guider les décisions politiques futures

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Au fil des chapitres, cet ouvrage apparaît comme une véritable somme de savoirs combinant les travaux de nombreux spécialistes du changement climatique et de ses impacts sur le bassin méditerranéen. Les observations et les analyses présentées confirment que cette région est un véritable creuset de diversité, tant du point de vue des environnements naturels que des conditions de vie des sociétés. Ainsi, il n'est pas surprenant que les impacts du changement climatique varient fortement d'un pays à l'autre, mais il en va de même des capacités d'adaptation et des possibilités d'atténuation face au changement. Les pays de la Méditerranée sont fortement liés par une mer commune qui a de tout temps favorisé la mobilité des hommes et la circulation des idées. L'expression « notre futur commun face au changement climatique » y prend une valeur toute particulière.

Depuis des millénaires, les sociétés humaines et leur environnement naturel ont évolué de concert dans le bassin méditerranéen. Les études paléoclimatologiques démontrent que l'Holocène a été rythmé par de brusques changements climatiques à l'origine de sécheresses importantes, qui ont probablement joué un rôle décisif dans l'évolution culturelle des sociétés méditerranéennes. Bien que le début du dernier millénaire ait été marqué par une période chaude (optimum climatique médiéval) jugée assez semblable au réchauffement récent, les « mégasécheresses » des dernières décennies sont vraisemblablement sans précédent. La vitesse du réchauffement que connaît le bassin est désormais supérieure aux moyennes mondiales, en particulier en ce qui concerne les températures estivales. On observe en outre un accroissement général des épisodes de températures et de précipitations extrêmes, une tendance qui devrait s'accélérer à l'avenir. La distribution spatiale exacte de ces changements reste toutefois incertaine. Le réchauffement de la Méditerranée est largement documenté, mais l'évolution future des schémas de circulation est encore débattue.

Les risques directs pour les personnes et les infrastructures de la Méditerranée sont liés au cycle de l'eau et tout particulièrement aux extrêmes hydrométéorologiques, comme les fortes pluies provoquant des crues éclair, mais également aux fortes houles et aux marées de tempêtes causées par les vents violents. Certaines années, les vagues de chaleur et les sécheresses réduisent les rendements agricoles et accroissent le risque de feux de forêt. Par leur nature même, ces extrêmes sont difficiles à confronter aux tendances temporelles, mais la création de bases de données et de programmes de recherche spécifiques a fait progresser nos connaissances de manière substantielle au cours de ces dernières années.

Le changement climatique interagit avec la pollution de l'air et de l'eau et les autres pressions d'origine anthropique (urbanisation, intensification de l'agriculture, expansion de l'industrie et des transports). La qualité de l'air continue de se détériorer dans l'ensemble du bassin méditerranéen. Les effets délétères de la pollution atmosphérique sur la santé humaine sont connus, mais des observations de meilleure qualité s'imposent dans de nombreuses régions. Bien que les pays méditerranéens soient aujourd'hui fortement exposés aux tempêtes de poussière et aux incendies, leurs effets exacts sont insuffisamment étudiés.

La mer Méditerranée est un réservoir primordial de biodiversité marine. Des millions de personnes dépendent de façon plus ou moins directe des services écosystémiques qu'elle fournit, et notamment de ses ressources halieutiques. L'ampleur des bouleversements écologiques attendus est encore incertaine. Toutes les projections basées sur les scénarios du GIEC confirment cependant que le réchauffement et l'acidification associés au changement climatique constituent une menace grave pour la biodiversité et l'exploitation durable des ressources de pêche dans la mer Méditerranée. La biodiversité terrestre est elle aussi exceptionnelle, spécialement dans les forêts, dans les nombreuses îles et sur l'ensemble du littoral. Les risques qui pèsent sur le fonctionnement de ces écosystèmes dérivent non seulement du changement climatique, mais également de la destruction et de l'utilisation non durable du paysage.

Le long des côtes, le principal défi est celui de la montée du niveau de la mer et des risques induits liés aux inondations et au retrait du rivage, qui devraient s'accentuer fortement au-dessus du seuil de 2 °C de réchauffement. De nombreuses ressources humaines, culturelles, industrielles et environnementales se concentrent à proximité des côtes. Une étude exhaustive des risques a montré que les rivages les plus vulnérables se trouvent dans les pays les plus pauvres et les moins développés. Ces pays ont besoin d'un important transfert de moyens économiques et technologiques en provenance des régions plus avancées.

Les ressources d'eau douce sont naturellement clairsemées dans une bonne partie de la région. Si le réchauffement, l'intensification de l'évaporation et la réduction des précipitations créent des pénuries d'eau supplémentaires, la multiplication des crues éclair peut d'un autre côté éroder et menacer la stabilité des sols. L'extraction non durable d'eaux souterraines et l'intensification de l'agriculture ont elles aussi un lien avec les problèmes observés, qu'elles contribuent à aggraver. Le climat extrêmement variable de la région méditerranéenne a donné naissance à un vaste éventail de pratiques agricoles. Si elle est préservée, cette diversité pourrait à l'avenir fournir des solutions d'adaptation. Le régime méditerranéen est célèbre pour sa valeur nutritionnelle et ses bienfaits sur la santé. Les projections révèlent des risques considérables pour la production alimentaire dans certaines zones du bassin. Bien que le Croissant fertile soit le berceau de l'agriculture, les agriculteurs ne sont pas nécessairement capables de surmonter les sécheresses longues et intenses, en particulier lorsque les conditions sociales et économiques génèrent un stress additionnel, à l'image de la sécheresse de 1998-2010 en Syrie. À l'heure actuelle, on ne sait pas avec certitude dans quelle mesure les sols méditerranéens pourront être gérés de façon plus durable dans l'espoir d'inverser des décennies de dégradation. En plus d'améliorer la sécurité alimentaire, de telles stratégies atténueraient pourtant les pertes de carbone.

Rares sont les études quantitatives à avoir examiné les impacts du changement climatique sur la santé en Méditerranée ; celles disponibles se limitent à certaines régions géographiques circonscrites du bassin. L'élucidation du lien entre le réchauffement, les nouveaux vecteurs, la pollution atmosphérique et d'autres facteurs exige une nouvelle approche résolument interdisciplinaire intégrant la médecine, la toxicologie, les sciences naturelles et sociales et l'ingénierie.

Étant donné la multiplicité des dangers naturels existants, dont certains peuvent être accentués par le changement climatique, la prévention des risques constitue une préoccupation majeure dans toute la région. D'importants progrès ont été réalisés dans les domaines de l'observation des conditions météorologiques et des inondations et des méthodes de prévision. Une meilleure communication avec la population et les services de secours est importante pour concevoir des mesures d'adaptation efficaces. Les événements catastrophiques ne peuvent être totalement évités, mais l'amélioration des systèmes d'alerte peut en limiter notablement les conséquences.

La Méditerranée est une frontière et un lieu de passage entre plusieurs régions très contrastées sur le plan tant économique que social. Cette particularité en fait aujourd'hui le théâtre d'un flux migratoire du sud vers le nord, avec les immenses souffrances humaines et la perte de vies humaines que cela suppose. Cette migration est le résultat de multiples facteurs sociaux et économiques, mais également du changement climatique, dont le rôle n'est encore compris que très imparfaitement par les chercheurs.

La plupart des contributions à cet ouvrage indiquent clairement que le changement climatique ne peut être compris sans une prise en compte plus approfondie de l'évolution parallèle de l'homme et de son environnement. Ce constat est valable dans la majorité des régions du globe, mais il apparaît que l'évaluation interdisciplinaire du changement doit atteindre un niveau de complexité supérieur en Méditerranée, en raison de l'ancienneté et de l'intensité de l'influence humaine. Il semblerait que les nombreuses mutations et les grandes disparités de la Méditerranée n'aient pas permis de mesurer pleinement l'importance des répercussions sociales du changement climatique pour les générations futures de la région. Loin de n'influencer que la nature, le changement climatique touche également l'ensemble du tissu économique, politique et social de la société méditerranéenne.

La responsabilité de la réduction des émissions de gaz à effet de serre et de l'optimisation de la capacité d'adaptation devra être assumée par tous les pays et tous leurs acteurs sociaux, dans le cadre d'une collaboration internationale étroite. Malgré l'abondance des connaissances et des observations, spécialement dans le Nord, aucune évaluation de pointe des risques et du potentiel d'adaptation à l'échelle de l'ensemble du bassin n'est disponible à l'heure actuelle. Une telle évaluation devrait inclure les résultats d'activités de modélisation régionalisées des émissions, du climat et des impacts, mais également considérer le savoir local et les expériences spécifiques dans le domaine de l'adaptation à la variabilité climatique de la région. Plus important encore, elle devrait prendre appui sur un partenariat Nord-Sud et Est-Ouest approfondi dans le bassin méditerranéen.

La création d'un tel pont entre les chercheurs et la société est l'objectif du MedECC (Mediterranean group of Experts of Climatic change), qui vise à :

1) Rassembler la communauté scientifique étudiant le changement climatique dans tout le bassin méditerranéen. Ceci suppose de jeter un pont entre les structures et programmes de recherche existants et de faciliter le partage de données sur les plateformes et forums actuels ou futurs.

2) Actualiser et regrouper les meilleures connaissances scientifiques sur les changements subis par le climat et l'environnement dans le bassin méditerranéen et les mettre à la disposition des décideurs, des principales parties prenantes et des citoyens.

3) Contribuer aux évaluations futures d'organismes internationaux (GIEC et IPBES, entre autres) dans le bassin méditerranéen.

4) Combler le fossé séparant la recherche de la prise de décision, de façon à contribuer à l'amélioration des politiques à l'échelle nationale, régionale et locale, en fournissant des évaluations scientifiques collectives sur des questions précises et en répondant aux demandes des décideurs.

5) Identifier d'éventuelles lacunes dans la recherche actuelle sur le changement climatique et ses impacts en Méditerranée et collaborer avec des organismes de financement afin de concevoir de nouveaux programmes de recherche comblant lesdites lacunes.

6) Contribuer au renforcement des capacités des scientifiques de tous les pays méditerranéens, en encourageant la formation, la recherche et le développement à travers la collaboration.

En tant que réseau régional, le MedECC pense être bien placé pour produire des rapports exhaustifs de la plus haute qualité sur le changement climatique et environnemental pour l'ensemble du bassin méditerranéen, en prenant également en compte les connaissances locales en différentes langues et la « littérature grise ». Grâce à des évaluations de ce type, nous espérons que des initiatives de recherche nationales et internationales telles que le programme français MISTRALS, qui a inspiré une partie du travail présenté dans le présent ouvrage, bénéficieront à la recherche intégrée sur les changements environnementaux dans le bassin méditerranéen.

# Postface

## From Paris to Marrakesh
## Rediscovering universalism

*Driss El Yazami*
President of CNDH (National Human Rights Council of Morocco)
Head of the Civil Society Activities of the 22nd Conference of Parties of the United Nations Framework Convention on Climate Change

The Paris agreement, adopted to great acclaim, marks a clear turning point in the long battle against the effects of climate change. No matter what reservations some people may voice, the international community has finally witnessed the acceptance of a multilateral framework accepted by countries with clearly divergent medium-term interests. It sets forth goals, including financial goals, but those objectives still need to be further defined, and steps for evaluation and revision still must be mapped out. It is clear that nothing can be taken for granted. The process of signing the agreement will be revealing in that regard. Nonetheless, the legal framework developed in Paris seems to have created real momentum.

Even more significant, in my opinion, are the signs of universal mobilization seen before, during, and after the Paris Summit.

For years, the battle for a transition to renewable energy has mainly been led by scientists, environmentalist non-governmental organizations, and a few international political figures, but today it seems to have gained new allies, and the expansion of the movement seems indisputable. Alongside these historically involved ‘experts’, new actors have signed up to the cause or have become more actively engaged in innovation, including development NGOs, businesses, regional and local governments, movements associated with various social forums, and others. Their growing involvement, though it can sometimes be hard to define, bears witness to the universal realization of the dangers climate change poses to the entire human race and of the true urgency with which an alternative policy must be adopted, one that is common to all parties (countries, social and economic actors, etc.), and that, while respecting the diversity of those parties, is still a product of their combined efforts and ideas.

I see this as highly promising news.

This interest in climate issues and the belief that everyone must respond in tandem are developing in a world which seems, almost everywhere, to have turned its back on universalism. In all parts of the world, those who subscribe to ideas of cultural, religious, or national 'specificity' seem to be riding high. No matter the particularities of a country's national history, 'the ancestors redouble their ferocity' (Kateb Yacine) and an emphasis is being placed on 'roots' — to the detriment of the universal values of human rights and the human rights movement, active notably since the end of World War II. The globalization of human rights seemed irreversible, but it is being attacked and undermined from all sides. Populist parties in Europe are calling for national bias and close-mindedness towards others. In the Muslim world, but in the Americas and India as well, religious references are being exploited. Devotees of ethnic 'purity' are everywhere. Mythical origins are being glorified, in opposition to the need for human brotherhood and the imperative of a universal solidarity that extends to the most vulnerable peoples and individuals.

It is against this backdrop that mobilization on climate change and the growing interest in environmental problems areextremely timely.

Of course, this mobilization is not the first of its kind. Major international movements rallying crowds across the world around a single cause have already occurred, and some remain active today. Internationalism was not born of the climate movement momentum. However, in this particular historic moment, it is the cause itself behind this mobilization that seems both new and promising.

All life on Earth is threatened, and to save it, countries, political regimes, and all other actors alike must respond together. Not a single part of the world can still be solely self-sufficient and avoid disaster. Even though historic responsibilities and the effects to come are unequally distributed, we must respond together. The climate emergency requires us, in a way, to 'remake humanity',

Of course, overcoming this challenge requires us to raise public awareness, negotiate agreements (like the one in Paris), define the ways and means of implementation, and finally, mobilize all actors, in all their diversity. However, to do so we especially need a shared foundation of values which transcend national self-interest and any temptation to retreat. As we face different forms of relativism, we must identify the 'inviolable foundation of rights' (Mireille Delmas-Marty) that will provide a universal basis for the current climate movements and, at the same time, create an unprecedented space for action in favour of universalism and human rights.

# Postface

## De Paris à Marrakech
## Retrouver l'universalisme

*Driss El Yazami*
Président du Comité national des droits de l'Homme (Maroc)
Chef du pôle de la société civile de la XXII[e] Conférence des Parties
de la Convention Cadre des Nations unies sur les changements climatiques

Adopté sous les ovations, l'accord de Paris constitue d'évidence un tournant dans la longue bataille contre les effets des changements climatiques. En effet, quelles que soient les réserves exprimées par certains, la communauté internationale dispose enfin d'un cadre multilatéral accepté par des États aux intérêts clairement divergents sur le moyen terme, avec des objectifs y compris financiers, même s'il reste à leur donner un contenu précis et à tracer les étapes d'évaluation et de révision. Rien n'est évidemment définitivement acquis. Le processus de signatures de l'accord sera à cet égard révélateur. Néanmoins, avec le cadre légal acquis à Paris, une réelle dynamique semble avoir été enclenchée.

Plus significative à mes yeux est l'esquisse d'une mobilisation universelle que nous avons perçue avant, durant et après le Sommet de Paris.

Porté depuis des années, principalement par des scientifiques, les organisations non gouvernementales environnementalistes et quelques figures politiques internationales, le combat pour une réelle transition énergétique semble avoir gagné de nouveaux alliés et ce mouvement semble incontestablement s'étendre. Aux côtés des « experts » historiques, de nouveaux acteurs sont en effet entrés en résistance ou sont de plus en plus actifs dans l'innovation, tels les ONG de développement, les entreprises, les collectivités territoriales, les mouvements impliqués dans les divers forums sociaux, etc. Leur implication croissante, bien que parfois difficile à articuler, témoigne d'une prise de conscience universelle des dangers pour l'humanité tout entière des changements climatiques et de l'absolue urgence d'adopter une véritable politique alternative, commune à tous (États, acteurs sociaux, économiques, etc.), respectueuse de leur diversité, mais agrégeant au final tous leurs efforts et réflexions.

C'est à mes yeux une très bonne nouvelle, riche de promesses.

Cet intérêt croissant pour la problématique du climat et la conviction de la nécessité d'une réaction commune à tous les hommes intervient en effet dans un monde qui semble, un peu partout, tourner le dos à l'universalisme. Dans toutes les régions du monde, les tenants de « la spécificité » culturelle, religieuse ou nationale semblent avoir le vent en poupe. Quelle que soit la particularité de l'histoire nationale des pays, « les ancêtres redoublent de férocité » (Kateb Yacine) et « les racines » sont mises en avant au détriment des valeurs universelles des droits de l'Homme et du mouvement qui les porte depuis, notamment, la fin de la Seconde Guerre mondiale. Alors qu'elle semblait irréversible, la mondialisation des droits de l'Homme est taraudée et minée de toute part. Partis populistes en Europe exigeant la préférence nationale et la fermeture face à l'autre, instrumentalisation du référent religieux dans le monde musulman mais aussi dans les Amériques et en Inde, tenants de « la pureté » ethnique un peu partout… l'origine mythifiée est glorifiée contre la nécessaire fraternité humaine et l'exigence d'une solidarité universelle, ouverte aux plus faibles d'entre les peuples et les individus.

C'est à cet égard que la mobilisation contre les changements climatiques et l'intérêt croissant pour les enjeux environnementaux sont plus que bienvenus.

Cette mobilisation n'est évidemment pas la première du genre. De grands mouvements internationaux rassemblant les foules en différents points du globe autour d'une cause unique ont déjà eu lieu ou sont encore actifs aujourd'hui. L'internationalisme n'est pas né avec cet élan sur le climat. Mais, dans ce moment historique particulier, c'est l'objet même de cette mobilisation qui semble à la fois inédit et prometteur.

C'est en effet l'ensemble de la vie sur Terre qui est menacé et le salut exige une réaction commune de chacun, pays, régimes politiques, tous types d'acteurs confondus. Aucune partie du monde ne peut plus se suffire à elle-même pour éviter la catastrophe. Même si les responsabilités historiques et les effets à venir sont inégalement répartis, c'est bien ensemble que nous nous devons de réagir. L'urgence climatique exige de nous en quelque sorte de « refaire humanité ».

Surmonter ce défi suppose bien évidemment d'amplifier la prise de conscience populaire, de négocier des accords (tel celui de Paris), d'en définir les modalités de mise en œuvre et, enfin, de mobiliser les acteurs dans leur diversité. Mais cela exige aussi et surtout un socle de valeurs communes, qui transcende les égoïsmes nationaux et les tentations de repli de toutes sortes. Face aux différentes formes de relativisme, il nous faut retrouver ce « socle indérogeable de droits » (Mireille Delmas-Marty), qui fournirait aux mobilisations en cours sur le climat un fondement universel et ouvrant, en même temps, un espace inédit d'action pour l'universalisme des droits de l'Homme.

# Address by HSH the Prince Albert II of Monaco

*International Conference "Savoirs en action pour un codéveloppement en Méditerranée", organized for the 350th anniversary of the Académie des sciences*

*MuCEM, Marseille*
29 September 2016

Mr Minister,

Mr Prefect,

Madam Permanent Secretary,

Your Excellencies,

Assembled Presidents,

Mr Rector,

Ladies and Gentlemen,

Dear Friends,

Allow me first of all extend my warm thanks to all those who have helped organise this major event and congratulate them on their choice of subjects to be addressed throughout the day.

It is a matter of great satisfaction for me to be here with you to celebrate the 350th anniversary of the Académie des Sciences, which promotes and protects the spirit of research, and has contributed towards scientific progress and its applications since 1666.

As a great fan of the sciences, like Colbert – the founder of your Académie – I was delighted to accept this invitation to map out a few avenues for reflection concerning the theme of the 'challenges facing the Mediterranean coast' – a topic which you will shortly address in your round table.

As a unique forum where people, cultures and religions come face to face, the Mediterranean has always been a place of exchanges which have given rise to whole civilizations.

In addition to being a cradle for these civilizations, the Mediterranean region also now at the centre of an unprecedented set of political, demographic and economic issues.

As the crossroads between three continents and a meeting place of three civilizations, the Mediterranean remains a forum for encounters, but is also prone to political, economic, environmental and cultural tensions. With this in mind, we can be justly proud of having launched so many initiatives in favour of cooperation and partnership, in order to strengthen those exchanges and, breathe new life back into the region's economies, despite the inequalities and imbalances among the region's various countries.

With a surface area of 2.5 million km², the Mediterranean represents 0.7% of the world's seas. Its coastlines extend over 46,000 km, in 22 countries with over 400 million inhabitants.

From a planetary perspective, this is a modestly-sized region, almost entirely enclosed and a major reservoir of biodiversity – it is home to over 25,000 plant species and 650 marine fish species, including 28% found exclusively here.

As a semi-enclosed sea, the Mediterranean is fragile and highly exposed to the effects of climate change and pollution.

This maritime region faces many constraints – be they ecological, anthropogenic, maritime, demographic or economic.

As the location of 30% of the world's maritime trade, including 22% of its oil trade, the Mediterranean is an extremely busy sea trading region, not to mention the leisure boating sector which has grown exponentially in recent years.

The Mediterranean coastlines have also seen significant growth in terms of population density: over 150 million inhabitants – almost a third of the population of the coastal countries. This figure has virtually doubled in the last 40 years and some of the coastal areas have witnessed rampant urbanization. We know that by 2025, half the Mediterranean coastline will consist of built-up areas.

While the Mediterranean can be justly proud of being the world's first tourist region, it must nevertheless cope with an influx of some 200 million tourists per year who come to enjoy their holidays on its coasts. And this figure looks set to grow still further by 2025, half most visitors staying within an area less than 100 metres from the coastline.

How can this influx be managed and the seasonal tourist economy structured, given that we are already witnessing significant increases in summer pollution of the seawater?

The number of inhabitants living on the coastline and the increase in summer populations only serve exacerbate the pollution from the land where in some countries – for example the Middle East and North Africa – there is a lack of drinking water, often brought about by the discharge of waste or used water.

Needs are outstripping infrastructural development on the coastline, particularly in terms of water treatment.

And so we are witnessing increasing pressure on our water supply, brought about by growing demand. All of which is being exacerbated by climate change.

Aquaculture is another source of pollution. With 110 kg of nitrogen, 12 kg of phosphorus and 450 kg of carbon emitted per tonne produced by fish farms, this represents a considerable challenge to be addressed as we seek out food security solutions.

In all these cases, wastewater, whether from cities, agriculture or rain, transports significant amounts of non-biodegradable solid and chemical waste. This waste spreads with the currents and winds, and constitutes a threat to marine fauna and flora.

And yet it is on the coast that marine biodiversity needs to be regenerated.

We can all agree that the scenario I have painted is not a happy one. But underestimating it is no longer an option.

We have entered an era in which most significant environmental change is brought about by men and women. Humanity has become a force for change on a planet-wide scale.

In the phrase coined by Dutch Nobel laureate Paul Crutzen, we are now living in the ‘Anthropocene’, meaning that in just a few generations, the influence of anthropogenic actions on the earth’s ecosystem has become the major factor.

The scientific studies being conducted today are beyond dispute: we simply must face up to our responsibilites.

Saving the planet – which was still seen as a minority-interest subject for the more daring spirits in Rio in 1992 – has become one of the key issues of the century. The climate question is an extremely potent symbol of the global threats which we must now manage and mitigate.

Beyond the question of the climate, other crucial topics are now beginning to attract the attention they deserve : in particular the questions of biodiversity, pollution and preserving water resources. Little by little, humanity is beginning to understand that these are matters of life and death.

They touch on the way we live and eat, but also on our health, security and – on a more general level – on economic and strategic balance throughout the world, and particularly here on the shores of the Mediterranean.

A few degrees more, a few species less, a couple of extra square kilometres in the desert – these are irreversible dramas, each of which will bring yet more tragedies and tales of exile, poverty and violence in their wake.

As we look into these climate and environmental issues, we are at last beginning to understand the central role of the seas and oceans. These vast stretches which for so long seemed incomprehensible, hostile, and devoid of interest other than for fishing are now – so science shows us – areas of great complexity, fragility and profound significance.

The international scene is now bearing witness to this new awareness. Major international gatherings are focusing on the issue, including of course the ongoing discussions at the UN about the high seas. As you know, the aim is to develop a "internationally binding legal instrument on the conservation and sustainable use of biological diversity" in the high seas.

These negotiations form part of a positive momentum, which has seen the emergence of several important milestones in recent months: the adoption last September of a sustainable development goal specific to the oceans; the decision of the IPCC to devote a forthcoming report to the relationship between the oceans and the climate; and the holding of a session dedicated to the subject at the COP 21 – an exercise which will be repeated at the COP22 in Marrakesh.

All of these are core areas to which I am deeply committed and to which I will be devoting unstinting effots with my Government and my Foundation.

On the national level, in Monaco I have introduced an unwavering energy transition policy designed to achieve carbon neutrality by 2050. We have undertaken several international cooperation missions regarding the environment and climate change. We have long been involved in drafting original policies to preserve the seas, like the RAMOGE accord signed with France and Italy for the prevention and management of marine pollution – an agreement now celebrating its fourth anniversary.

This work is complemented by that of my Foundation which has spent the last ten years fighting climate changes and its impacts, in order to preserve biodiversity, manage water and combat desertification.

All of these initiatives and actions – everything we are doing for the environment – is made possible by science.

One of the missions with which the Academy is entrusted is to monitor the quality of teaching and strive to integrate the findings from scientific developments into the general contemporary culture. I can only express my wholehearted support for this aim.

The decisions leaders make today must be based on our scientific awareness.

In light of the complex and barely perceptible realities of the climate, science brings us awareness and gives us power.

It is science that has convinced us of the urgency to act, it is in its name that we try to persuade those around us, and it is science that will help us construct a new development paradigm: a model based on innovative techniques which respect the environment.

We are all collectively indebted to scientists. Without science, none of the progress made in recent years would have been possible.

This is also why Monaco has long been supporting research as a key dimension of its policy. This has led to – amongst other things – the development of its science centre, the welcoming of the AIEA Marine Environmental Studies Laboratory supporter of research and also my Foundation's commitment to founding programmes and expeditions. And in the same spirit, we have strongly advocated for the IPPC to draft a report on the oceans and the cryosphere.

But our debt to science does not end there. While we owe much to researchers and their discoveries and inventions and the perspectives they open up, we should, I believe, draw inspiration from their methods.

Because both discovery and invention are the offsring of what makes science great: doubt. It is doubt that drives us to explore new avenues, try things out and seek new horizons.

Today I am convinced that our political and economic leaders, like all environmental leaders, must draw inspiration from this key state of mind. At all levels, we must question our habits, our lazy assumptions and our comfortable ways of thinking.

This is exactly what I am trying to do with my Foundation, as a complement to the activities my Government has been tasked with implementing.

This also underlies my attempts to bring together economists, scientists, politicians and environmentalists in conjunction with my Foundation.

And finally it also explains my search for new practical solutions to preserve our seas, oceans and climate. I mentioned the ongoing talks at the UN which are exploring new approaches to understanding the ocean, but I could also cite other initiatives, such as the protected marine reserves for which I have been fighting for many years. These structures constitute an appropriate framework for managing the seas, and only they can facilitate the joint economic development of the coastal populations and the preservation of the ecosystems.

This is why we have, together with the French Government, created a Trust Fund dedicated to the creation and strengthening of marine protected areas in the Mediterranean. And it is why we are currently working on the reform of the Pélagos sanctuary for the protection of sea mammals along the French, Italian and Monaco coastlines.

Here too, the key is to innovate, question existing received wisdom and devise new solutions that will help us save our seas and our climate.

It is now time for your exchanges to take place, so that you can discuss the future of the Mediterranean Basin in light of its history and its past, touching not only on the limitations but also on the opportunities ahead.

I would like to thank the Académie once again for its initiative, but also its partners, the Groupe Inter académique pour le développement (GID), the French National Research Institute for Sustainable Development (IRD) and the Union for the Mediterranean for this encounter, here at the MuCEM – a fitting venue to discuss the Mediterranean, its importance and its protection.

I hope therefore that the Mediterranean will inspire us – just as it has inspired so many great minds down the centuries, so that we may develp sustainable solutions and practices to help us achieve the best possible balance between human development and the preservation of our beloved Mare Nostrum.

Thank you.

# Allocution de SAS le Prince Albert II de Monaco

*Rencontre internationale « Savoirs en action pour un codéveloppement en Méditerranée » à l'occasion du 350e anniversaire de l'Académie des sciences*

*MuCEM, Marseille*
29 septembre 2016

Monsieur le Ministre,

Monsieur le Préfet,

Madame le Secrétaire Perpétuel,

Excellences,

Messieurs les Présidents,

Monsieur le Recteur,

Mesdames et Messieurs,

Chers Amis,

Je veux d'abord remercier toutes les personnes qui ont contribué à l'organisation de cet événement d'importance et les féliciter pour le choix des sujets qui seront abordés durant cette journée.

C'est une grande satisfaction pour moi d'être ici avec vous pour célébrer les 350 ans de l'Académie des Sciences, qui encourage et protège l'esprit de recherche, et contribue aux progrès des sciences et de leurs applications depuis 1666.

Attaché aux sciences, comme le fondateur de votre Académie – Colbert –, c'est avec infiniment de plaisir que j'ai accepté de tracer quelques pistes concernant « les défis du littoral méditerranéen », thème dont vous allez débattre en table ronde tout à l'heure.

Lieu de rencontre privilégié des hommes, des cultures et des religions, la Méditerranée a toujours été un espace d'échanges qui a permis l'émergence de civilisations.

Berceau de ces civilisations, elle est aujourd'hui au centre d'enjeux politiques, démographiques et économiques sans précédent.

Carrefour à la lisière de trois continents et de trois aires de civilisations, la Méditerranée demeure une zone de contacts mais également de tensions, politiques, économiques, environnementales ou culturelles. A ce titre, nous devons nous féliciter des nombreuses tentatives de coopération et de partenariat qui sont lancées pour renforcer les échanges et redynamiser les économies, malgré les clivages et les déséquilibres entre les Etats riverains.

D'une superficie de 2,5 millions de km², la Méditerranée représente 0,7 % de la surface des mers du globe. Ses côtes s'étendent sur 46 000 km, le long de 22 pays peuplés de plus de 400 millions d'habitants.

De taille modeste à l'échelle de la planète, elle est quasiment fermée et constitue un réservoir majeur de biodiversité qui accueille plus de 25 000 espèces de végétaux, 650 espèces de poissons – dont 28 % seraient introuvables ailleurs.

Par sa nature même de mer semi-fermée, la mer Méditerranée est fragile, très sensible aux modifications climatiques et aux pollutions.

Or, l'espace maritime méditerranéen est menacé par diverses contraintes, qu'elles soient écologiques, anthropiques, maritimes, démographiques ou économiques.

Support de 30 % du commerce maritime mondial dont 22 % de trafic pétrolier, la mer Méditerranée est très fréquentée en matière de commerce maritime. S'y ajoute la navigation de plaisance dont l'augmentation ces dernières années est exponentielle.

Le littoral de la mer Méditerranée connaît, par ailleurs, une évolution importante de densité de ses populations : plus de 150 millions d'habitants, soit quasiment un tiers de la population des pays riverains. Ce chiffre a quasiment doublé au cours des quarante dernières années et les rives sont soumises, pour certaines, à une urbanisation galopante. Nous savons qu'à l'horizon 2025, la moitié du littoral méditerranéen devrait être construit.

Si la région méditerranéenne peut s'enorgueillir d'être la première région touristique du monde, elle doit toutefois faire face à un afflux de quelque 200 millions de touristes qui, chaque année, viennent en villégiature sur ses côtes. Ce chiffre devrait encore augmenter à l'horizon 2025 avec une majorité localisée dans une zone inférieure à 100 m du rivage.

Comment gérer cet afflux et structurer une économie touristique saisonnière alors que nous sommes déjà témoins d'une augmentation très sensible, en été, de la pollution des eaux marines ?

Le nombre d'habitants sur les rives et le surcroît estival de population augmentent le phénomène de pollution d'origine terrestre avec, pour certains pays – comme par exemple ceux du Moyen-Orient et d'Afrique du Nord – un manque d'eau potable, laquelle est souvent affectée par le rejet de déchets ou d'eaux usées.

Sur la bordure littorale, l'accroissement des besoins dépasse souvent le développement des infrastructures, notamment des systèmes d'épuration.

Ainsi assiste-t-on à des pressions sur les ressources en eau, engendrées par des demandes croissantes. Et ces tendances sont exacerbées par les impacts du changement climatique.

Une autre source de pollution provient de l'aquaculture. Avec 110 kg d'azote, 12 kg de phosphore et 450 kg de carbone émis par tonne produite dans les fermes aquacoles, elle n'est pas à négliger au titre des défis à analyser alors que nous cherchons des solutions de sécurité alimentaire.

Dans tous les cas, les eaux usées qu'elles soient urbaines, agricoles ou pluviales charrient et drainent des déchets solides ou chimiques tous peu biodégradables. Ces déchets se répandent au gré des courants et des vents ; et constituent une menace pour la faune et la flore marines.

Or, c'est justement sur le littoral maritime que la biodiversité marine se régénère.

Les constats que je viens d'énoncer, vous en conviendrez, sont peu réjouissants, je vous le conçois, c'est vrai. Mais nous ne pouvons plus les sous-estimer.

Nous sommes entrés dans une ère où les principales modifications de l'environnement sont provoquées par l'homme, l'humanité étant devenue une force de modification à l'échelle de la planète.

Comme l'annonçait le nobélisé néerlandais Paul Crutzen, dans son néologisme, nous assistons à l'« anthropocène », ce qui signifie qu'en quelques générations, l'influence des activités anthropiques sur le système terrestre est désormais prépondérante.

Aujourd'hui, des études scientifiques ont été menées, dont les résultats ne sont pas remis en cause ; nous devons prendre la mesure de nos responsabilités.

La préservation de la Planète, qui passait jusqu'au sommet de Rio de 1992 pour un sujet mineur, porté seulement par quelques esprits audacieux, est devenue l'un des enjeux majeurs de ce siècle. La question climatique en est l'un des puissants symboles, symbole des risques globaux qu'il nous faut aujourd'hui gérer et limiter.

Au-delà même du climat, d'autres sujets essentiels commencent à recueillir l'attention qu'ils méritent, en particulier les questions de biodiversité, de pollution, ou de préservation des ressources en eau. Peu à peu, l'humanité comprend qu'il s'agit-là de problématiques vitales pour elle.

Elles touchent en effet à notre cadre de vie et à notre alimentation, mais aussi à notre santé, à notre sécurité et, plus globalement, à tous les équilibres économiques ou stratégiques de ce monde et plus particulièrement des rives de la Méditerranée.

Quelques degrés en plus, quelques espèces en moins, quelques kilomètres carrés de désert supplémentaires, ce sont pour beaucoup des drames irréversibles, entraînant leur lot de tragédies, d'exils, de misères, de violences.

Au cœur de ces enjeux climatiques et environnementaux, nous comprenons enfin le rôle central des mers et des océans. Ces vastes étendues qui, longtemps, ont semblé à l'homme intangibles, hostiles et dénuées d'intérêt autre que la pêche, révèlent, grâce aux travaux de la science, leur complexité, leur fragilité et leur importance.

L'actualité internationale témoigne également de cette nouvelle conscience. De grands rendez-vous internationaux s'y consacrent, comme bien sûr les négociations actuellement en cours à l'ONU sur la haute mer. Il s'agit, vous le savez, de rédiger un « instrument international juridiquement contraignant sur la conservation et l'utilisation durable de la diversité biologique » en haute mer.

Ces négociations s'inscrivent dans une dynamique positive. Elle a été marquée au cours des derniers mois par plusieurs étapes importantes : l'adoption, en septembre dernier, d'un objectif de développement durable spécifique aux océans ; la décision du GIEC de consacrer un prochain rapport au rôle des océans pour le climat ; ou encore la tenue d'une session dédiée aux océans au cours de la COP21 – initiative qui sera reconduite, lors de la COP 22 à Marrakech.

Tous ces chantiers sont au cœur de mon engagement. Je m'y implique sans relâche, avec mon Gouvernement et ma Fondation.

Au niveau national, j'ai mis en place à Monaco une politique résolue de transition énergétique, avec l'ambition de parvenir à la neutralité carbone dès 2050. Nous avons engagé de nombreuses missions de coopération internationale centrées autour de l'environnement et du changement climatique. Depuis longtemps, nous avons conçu des politiques originales de préservation des mers, comme l'accord RAMOGE signé avec la France et l'Italie pour la prévention et la gestion des pollutions marines, dont nous venons de célébrer les quarante ans.

Cette action est complétée par celle de ma Fondation, qui agit depuis dix ans contre le changement climatique et ses effets, pour la préservation de la biodiversité et pour la gestion de l'eau et la lutte contre la désertification.

Toutes ces initiatives, toutes ces actions, tout ce que nous accomplissons pour l'environnement, nous le faisons grâce à la science.

L'une des missions confiées à l'Académie est de veiller à la qualité de l'enseignement et d'œuvrer pour que les acquis du développement scientifique soient intégrés dans la culture des hommes de notre temps. Je ne peux que souscrire à cette orientation et je la plébiscite.

La prise de décisions des leaders, aujourd'hui, doit largement se fonder sur la prise en compte de la science.

Face aux réalités complexes et difficilement perceptibles du climat, la science nous a donné la conscience et la puissance.

C'est par la science que nous avons été convaincus de l'urgence d'agir, c'est en son nom que nous parlons pour convaincre nos contemporains, et c'est aussi par elle que nous avons les moyens de construire un autre modèle de développement. Un modèle fondé sur des techniques innovantes et plus respectueuses de l'environnement.

Nous devons aux scientifiques une gratitude collective. Sans la science, aucune des avancées de ces dernières années n'aurait été possible.

C'est la raison pour laquelle Monaco a depuis longtemps fait du soutien à la recherche un axe important de sa politique avec, notamment, le développement de son centre scientifique, l'accueil du laboratoire d'environnement marin de l'AIEA, mais aussi l'engagement de ma Fondation sur des programmes et expéditions. C'est dans le même esprit que nous avons conduit un travail important de persuasion en faveur de l'établissement par le GIEC d'un rapport consacré aux océans et à la cryosphère.

Notre dette envers la science ne s'arrête pas là. Si nous sommes redevables aux chercheurs de leurs découvertes, de leurs inventions et des perspectives qu'elles ouvrent, nous devons aussi, je crois, nous inspirer de leur démarche.

Car la découverte, comme l'invention, naissent de ce qui fait la grandeur de la science : le doute. C'est le doute qui pousse vers d'autres chemins, suscite des tentatives, ouvre de nouveaux horizons.

Je suis aujourd'hui convaincu que les dirigeants politiques ou économiques, comme tous les acteurs environnementaux, doivent s'inspirer de cette posture d'esprit essentielle. A tous les niveaux, nous devons remettre en question nos habitudes, nos paresses, nos conforts.

C'est ce que je tâche de faire avec ma Fondation qui agit en complément de l'action que j'assigne à mon Gouvernement.

C'est aussi ce que je tâche de faire en associant, dans le cadre de ses actions, des acteurs économiques et scientifiques, politiques et environnementaux.

C'est enfin ce que je tâche de faire en cherchant de nouvelles solutions concrètes pour préserver nos mers, nos océans et notre climat. J'ai évoqué les négociations onusiennes en cours, qui doivent explorer de nouvelles approches des enjeux océaniques. Mais je pourrais aussi citer d'autres initiatives, comme les aires marines protégées, pour lesquelles je milite depuis de nombreuses années. Ces structures offrent un cadre approprié de gestion des mers, seul à même de permettre à la fois le développement économique des populations côtières et la préservation des écosystèmes.

C'est pourquoi nous avons créé avec le Gouvernement français un Fonds fiduciaire dédié à la création et au renforcement d'aires marines protégées en Méditerranée. C'est pourquoi aussi nous travaillons actuellement à la réforme du sanctuaire Pélagos pour la protection des mammifères marins au large des côtes françaises, italiennes et monégasques.

Là encore, il s'agit d'innover, de remettre en cause les anciennes recettes et d'en inventer de nouvelles, qui nous permettront de sauver nos mers et notre climat.

Je vais maintenant laisser la place à vos échanges afin d'envisager l'avenir du bassin méditerranéen au regard de son histoire et de son passé, de ses contraintes mais aussi de ses opportunités.

Je tiens à remercier encore l'Académie pour son initiative, mais aussi remercier ses partenaires, le Groupe inter académique pour le développement (GID) et l'Institut de recherche pour le développement (IRD) ainsi que l'Union pour la Méditerranée de cette rencontre, dans ce lieu du MuCEM qui se prête aux réflexions sur la mer méditerranée, son importance et sa protection.

J'espère donc que la Méditerranée saura nous inspirer, comme elle a inspiré tant de grands esprits à travers l'histoire, afin de valoriser les solutions et les pratiques durables qui permettront de mieux concilier le développement humain et la préservation de cette MARE NOSTRUM qui nous est si chère.

Je vous remercie.

# List of acronyms

| | |
|---|---|
| ACCOBAMS | Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea |
| ADRIMED | Aerosol Direct Radiative Impact on the regional climate in the Mediterranean region |
| AED | Atmospheric evaporative demand |
| AMO | Atlantic Multidecadal Oscillation |
| AOGCM | Atmosphere-ocean general circulation models |
| AORCM | Atmosphere-ocean regional climate models |
| AVISO | A reference portal in alimetry |
| BL | Boundary layer |
| BVOC | Biogenic volatile organic compound |
| CMIP | Coupled Model Intercomparison Projects |
| CORDEX | Coordinated Regional Climate Downscaling Experiment |
| DAD-IS | Domestic Animal Diversity Information System |
| DRF | Direct radiative forcing |
| EC | elemental carbon |
| EMDW | Eastern Mediterranean deep water |
| EMT | Eastern Mediterranean Transient |
| ENM | Ecological Niche Model |
| ENSO | El Niño-Southern Oscillation |
| E-OBS | high-resolution gridded data set of daily climate over Europe |
| ETCCDI | Expert Team on Climate Change Detection, Monitoring and Indices |
| EU | European Union |
| EVI | Enhanced Vegetation Index |
| FAO | Food and Agriculture Organization |

| | |
|---|---|
| FF | Flash floods |
| GCM | Global climate model |
| GCM | General circulation model |
| GFCM | General Fisheries Commission for the Mediterranean |
| GFCS | Global Framework for Climate Services |
| GHG | Greenhouse gases |
| GLAM | Gradient in Longitude of Atmospheric constituents in the Mediterranean basin |
| HPE | Heavy precipitation events |
| ICZM | Integrated coastal zone management |
| IPBES | Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services |
| IPCC | Intergovernmental Panel on Climate Change |
| IUCN | International Union for the Conservation of Nature and Natural Resources |
| LEK | Local ecological knowledge |
| MCA | Millennium Challenge Account |
| MCS | Mesoscale convective systems |
| MEA | Middle East Area |
| MedCOF | Mediterranean Climate Outlook Forum |
| MENA (region) | Middle-East North-Africa |
| MINOS | Mediterranean Intensive Oxidant Study |
| MTE | Mediterranean-type ecosystem |
| MPA | Marine protected area |
| MTC | Mean temperature of the catch |
| NAO | North Atlantic Oscillation |
| NMHC | Non methane hydrocarbons |
| NDVI | Normalized Difference Vegetation Index |
| NPF | New particle formation |
| OVOC | Oxidized volatile organic compound |
| PAH | Polycyclic aromatic hydrocarbons |
| PAR | Photosynthetically active radiation |
| PDO | Protected Designation of Origin |
| PES | Post-event surveys |
| PSM | Plant secondary metabolite |
| PMV | *Plan Maroc Vert* (Moroccan Green Plan) |

| | |
|---|---|
| PMF | Positive matrix factorization |
| POP | Persistent organic pollutant |
| RCC | Rapid climatic change |
| RCCI | Regional climate change index |
| RCM | Regional climate model |
| RCP | Representative concentration pathway |
| RCSM | Regional climate system models |
| ROV | Remotely operated vehicle |
| SLR | *Sea level rise* |
| SOA | Secondary organic aerosol |
| SOP | Special observation period |
| SPEI | Standard precipitation evapotranspiration index |
| SSS | Sea surface salinity |
| SST | Sea surface temperature |
| SWC | Soil and water conservation measures |
| SWI | Soil water index |
| SY | Sediment yields |
| TEE | Throughfall exclusion experiment |
| TOA | Top of the atmosphere |
| TRAQA | Transport and air quality |
| UNWTO | *United Nations World Tourism Organization* |
| VOC | Volatile organic compound |
| WeMO | Western Mediterranean Oscillation |
| WMO | World Meteorological Organization |
| WUE | Water use efficiency |
| VAI | Vegetation anomaly index |
| VCI | Vegetation condition index |

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The contributors to each chapter are listed in alphabetical order.

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The preface, introductory pages, chapter summaries and conclusion are published in two languages: French and English.

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