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The Role of Cloud Tracking and Passive Microwave Techniques in the Short-term Prediction of Flood Hazard on a Regional Scale

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Abstract. The role of remote sensing in enhancing the monitoring capabilities and the short-term prediction of the risk of flooding on a regional scale is addressed in this paper by means of the application of storm identification and cloud tracking techniques to a few case studies where cluster analysis based on infrared satellite imagery is used as the primary source of information. Polar satellite sensors, which provide passive microwave images, were also proposed in the literature for application in flood forecasting operational problems, though the accuracy of passive microwave techniques is only acceptable when rainfall estimates are integrated over quite large spatial and temporal scales. Climatological studies are well suited to make use of such data while the measure of instantaneous rainfall is still lacking of an adequate validation. A theoretical and numerical framework for the assessment of the reliability of passive microwave estimates of instantaneous rainfall within the typical resolution scales of polar satellite sensors is provided in the paper.

Sommario. Il ruolo delle tecniche di monitoraggio da sensori remoti nell'incrementare le potenzialità di previsione a breve termine del rischio di inondazione a scala regionale è analizzato nel presente lavoro attraverso l'applicazione di tecniche di identificazione ed inseguimento dei corpi nuvolosi ad alcuni casi di studio in cui le immagini satellitarie nella banda dell'infrarosso termico sono utilizzate come principale strumento di monitoraggio. In letteratura viene inoltre proposta l'utilizzazione, in applicazioni operative di previsione delle inondazioni, di sensori alle microonde passive montati su satelliti ad orbita polare: l'accuratezza di tali tecniche è tuttavia accettabile solo quando le stime di precipitazione vengono integrate su ampie scale spaziali e temporali. Mentre l'uso di tali tecniche per studi climatologici è di notevole utilità, la misura della precipitazione alle piccole scale spazio-temporali necessita ancora di un adeguato processo di validazione. Nel presente lavoro viene proposto un approccio teorico per la stima dell'affidabilità di tali stime di precipitazione alle scale tipiche della risoluzione spaziale del sensore.

Key words: Remote sensing, Rainfall, Flood forecasting, Hydrometeorology.

1. Introduction

The noticeable research effort recently undertaken by the scientific community towards the detection of some clear evidence of changes in climate characteristics on a planetary scale points to a deeper understanding of the physical processes that are likely to play, at the land–atmosphere interface, any significant role in affecting climate through an interaction with the energy balance of the earth. The enhancement of the present capabilities to obtain reliable measurements of the hydrometeorological variables involved is one of the outstanding research objectives in hydrology, which are expected to provide the experimental basis where the evidence of trends or modifications can be soundly discussed and eventually enucleated from the underlying variance characteristics of the processes observed. Among these variables rainfall is the most familiar and commonly measured among hydrologists, at least where traditional rain gauge networks are concerned and the distribution of space–time rainfall over the land areas is investigated.

Remote sensing techniques are largely proposed to enable rainfall monitoring over large spatial domains [1], as providing the opportunity of measuring precipitation over the sea areas – which make up two thirds of the total surface area of the earth – where no traditional rain gauge measurements are actually available. In this view passive microwave sensors – presently flying on board polar orbiting satellites at low altitudes – seem to provide the most reliable estimates of the average rainfall intensities on the ground [7]. In particular, in consideration of the resolution of the scans (15 × 15 km at best) and the timing of satellite passages (daily), such measurements have been widely used for rainfall climatology analysis. Indeed, the reliability of the estimates is acceptable when integrated over large spatial and temporal scales while the measure of rainfall depths over small time scales is still lacking adequate validation.

However, the operational resolution of the available sensors is still too rough to fulfill rainfall monitoring requirements at sub-grid scales: a large effort is being devoted by hydrologists and remote sensing scientists to the development and validation of precipitation retrieval algorithms able to provide estimates of the so-called instantaneous rainfall rates for possible use in flood forecasting through the prediction of extreme values for small spatial scales. In this case, the areal averaged nature of remotely sensed estimates with their implicit, but unperceived, time scale [3] is not very significant in supporting the validation of any simulated rainfall field against the 'measured' data. At the same time, the rain gauge point measurements present a high degree of variability when averaged over short time intervals and the estimation of the 'true' rainfall distribution in space is still affected by much uncertainty.

2. The Use of Cloud Tracking Techniques

Cloud tracking techniques as applied in this work use the algorithms for cluster analysis initially described by Filice *et al.* [5], [6]; recent developments can be found in Lanza and Siccardi [11] and Bolla *et al.* [2]. The algorithms are suitable for the analysis of satellite imagery in the thermal infrared (IR) band and are thus reliable for the synoptic-large mesoscale investigation. The images, as provided half hourly by the Meteosat radiometer in the B format (i.e. covering the European, North African and Middle Eastern region) are georeferenced, for use in the present work, in a latitude–longitude system and the layout of coastlines is superimposed. A window over the Mediterranean area from 30°N to 60°N and from 20°W to 30°E, is also extracted.

In view of the clustering process a large amount of data, describing for each image the radiance temperature of clouds at the low and middle elevations, is not essential for this analysis. Low and middle elevation clouds are thus filtered out from the images, with a suitable pre-processing, in order to speed up the clustering procedure and to avoid too much noise in the results. Segmentation is performed by means of a fixed threshold, pre-defined on the basis of the climatological and meteorological characteristics of the area. Processed images show only the highest level portion of the cloud coverage, namely that which is associated with the highest probability of heavy rainfall. Usually a threshold at 253°K is set at the middle latitudes for precipitating clouds during the fall season even if research is now confirming that fixed thresholds are often too crude to provide the best possible results. Operationally, each pixel x_j in a single IR image (only pixels bounded by a threshold isotherm $T_0 = 253°\text{K}$ are considered) is associated with a radiance value x_{3j}, and two geographical attributes x_{1j}, x_{2j} (Cartesian coordinates). The approach is that of performing a fully automated identification of the main clusters in each image using algorithms belonging to optimization methods, namely the K-mean method [4].

Any correspondence between clusters identified in two subsequent images is automatically detected using different techniques. However, usually the analysis is concentrated over a particular region where a potentially hazardous cloud system is identified. On the basis of the assumption that what we do identify in the infrared Meteosat images is not a well defined physical entity but rather the result of several different constraints acting on an evolving meteorological scenario, the following consideration on the eventual tracking of such entity holds: the traditional approach to the analysis of the dynamics of cloud systems by establishing the correspondence among a selected cluster of MCC pixels (Mesoscale Convective Complexes – see Maddox, [13]) in two successive images by means of some correlation matrix becomes unsuitable when it is accepted that no physical correspondence between these points actually exists. Nevertheless some kind of regularity in the successive locations and in the evolution of segmented MCC in the Meteosat images can be recognized. In the described approach the analysis of the evolution in time of some MCC parameters defining a very general shape able to represent the area of highest probability of heavy precipitation in each single image is addressed. The elliptical shape has been chosen in this work because of its features of simplicity, adaptability and good approximation of the observable MCC shapes. The elliptical equivalent shape is defined as the elliptical shape which presents the centre coincident to the MCC centroid, the same direction of the principal axes and the same principal inertial radius.

The application of the cloud tracking techniques described is carried out by addressing a case study of MCC development and evolution which has been selected, among several observed and analyzed, to be presented within the present work. Reference is made to the extreme meteorological conditions observed during the autumn of 1992 over the Mediterranean area. In the analyzed case (namely the event which developed on September 22nd–23rd, 1992 over the coastal regions of southern France and northern Italy) the evolution of the phenomena was quite stable and the main convective structure, identified by the area of coldest cloud top temperatures, was clearly clustered giving the opportunity of useful application of cloud tracking techniques as described above. The sequence of Meteosat images shows that the large MCC which was responsible for intense precipitation and floods over southern France and northern Italy originated in the early morning of September 22nd over southern France. In the following hours the system moved quite slowly towards northern Italy, covering the Liguria region of Italy in the afternoon of September 22nd, and producing floods in the small size catchments (50–100 km^2) near the city of Savona. The MCC shows a persistence over the Liguria region until the afternoon of September 23rd. The event was later mainly located over the Tyrrhenian sea and the MCC reached southern Italy before the definitive dissolution.

The output of the storm identification and cloud tracking analysis as applied to the described case study is summarized in Figures 1 to 3. Note that, in Figure 1, the center of mass shows a quite irregular path against the quite stable evolution of the whole system. This is due to the physical nature of the entity we are actually tracking along as, in each image, the cluster is a different object with a quite independent shape and areal coverage. The observed path is thus the effect of the superposition of two main atmospheric components: the overall dynamics of the system (quite stable in both cases) and the variability of the location of the center of mass which is mainly a function of the growth or dissolution of different small scale formations within the cluster resulting from the turbulent nature of convection mechanisms which generate the cluster. This is easily detectable by comparing the graphs in Figures 1 and

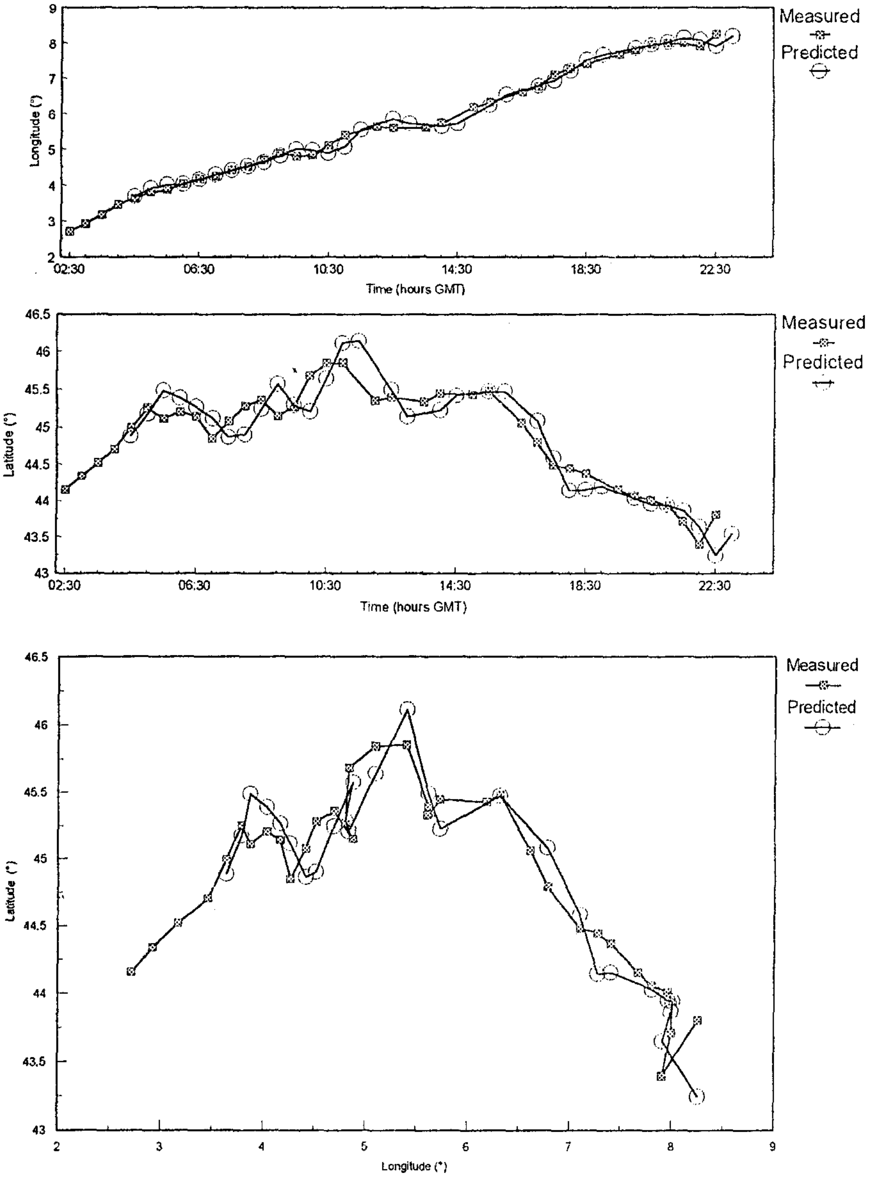

Fig. 1. Event of September 22nd, 1992. Evolution of the MCC in terms of path of the centroid and predictions at one step in advance from 02:30 GMT of the 22nd to 00:00 GMT of September 23rd.

2: the most significant changes in the location of the center of mass correspond to the largest variations in the cluster areal coverage.

An example of the prediction capability of the applied cloud tracking technique is shown in Figure 3 where the results of the procedure are represented by means of an equivalent elliptical shape superimposed upon the observed cluster. The ellipses drawn in thick black are those at the present time – i.e. representing the schematization of the cluster which is shown in the same picture – while those drawn in thin black are representative of the prediction made one step earlier with reference to the present time. The dashed lines are the prediction made two steps earlier. The effect of the growth and dissolution of some portion of the cluster

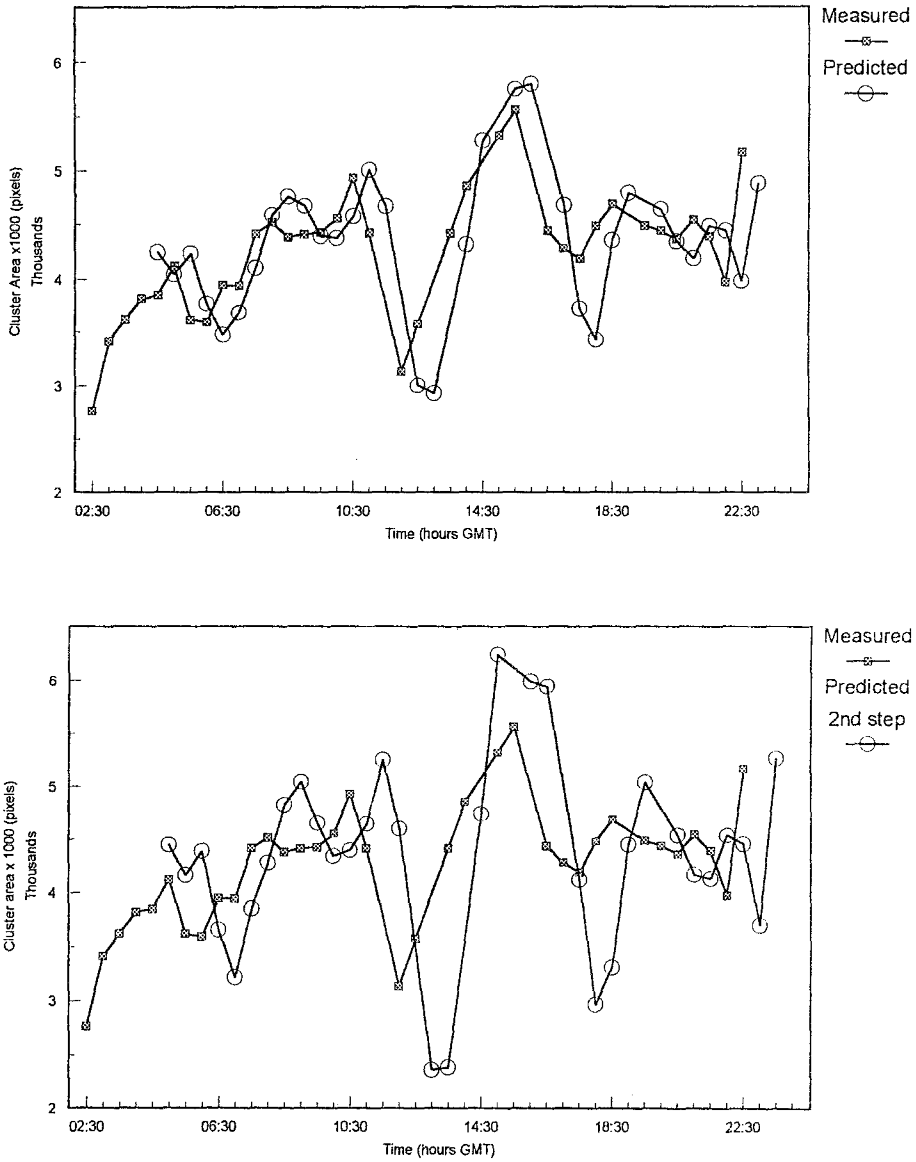

Fig. 2. Event of September 22nd, 1992. Evolution of the MCC area in terms of path of number of clustered pixels and predictions at one and two steps in advance from 02:30 GMT of the 22nd to 00:00 GMT of September 23rd.

is detectable in the second picture of Figure 3 where a significant difference between the predicted and the observed equivalent ellipses is quite evident.

3. The Hydrological Perspective

3.1. THE PRECIPITATION FIELD

The internal structure of the precipitation field within the MCC holds spots of high rainfall intensity with spatial scales of a few square kilometers and time scales in the order of one hour or less. Even when dealing with extreme events the actual distribution of such small scale features of the precipitation field in space and time is often ignored against the assessment

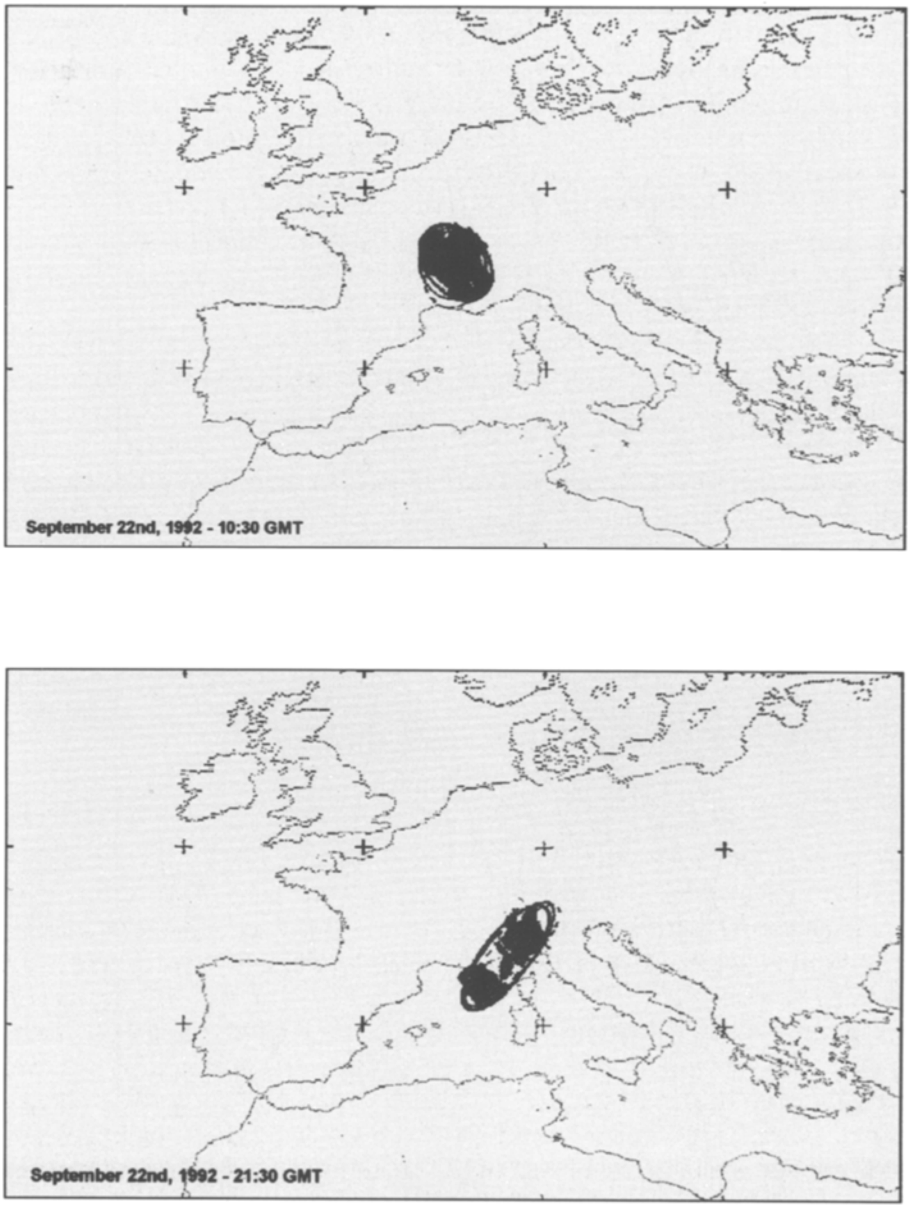

Fig. 3. Event of September 22nd, 1992. MCC identification and equivalent ellipses at 10:30 GMT and 21:30 GMT.

of the average rainfall over the catchment area. In contrast, flash floods typically occur when some kind of 'resonance' exists between the scales of heavy rainfall intensity and the geomorphologic scales of the underlying drainage structures [10].

While in the case of Meteosat images quantitative instantaneous rainfall retrieval has been recently recognized as being largely unreliable and storm identification and cloud tracking techniques only deal with cloud coverage characteristics, the use of passive microwave satellite sensors for the remote sensing of precipitation still gives rise, from a hydrological perspective, to a series of considerations about the influence of the actual distribution of rainfall intensities within the Field Of View (FOV) of the sensor, defined as the physical area on the ground surface from which the information is collected by the sensor as one single value and is associated with a pixel in the satellite images of the scanning radiometers on the satellite measurements. Let us take into consideration, for instance, the SSM/I (Special Sensor Microwave Imager) radiometer which is presently flying on board a NASA-DMSP polar orbiting satellite and providing images of each single footprint on the surface of the earth with a temporal resolution of 12 hours. The best resolution in space is obtained at the scanning frequency of 85 GHz and results in the order of 15 × 15 km; the use of a multifrequency approach – which provides a better insight into the micro physics of the observed clouds – yields the resolution of about 30 × 30 km, that is typical for the scanning at 37 GHz.

It is evident that the precipitation field is not uniform at all within the FOV of the sensor, presenting intermittency effects and high intensity spots which may be differently distributed even under the same overall characteristics of the field (mean value over the pixel area, spatial correlation structure, ...). In this view the crucial point is whether the satellite measurement of precipitation actually represents the average rainfall intensity over each pixel, given that the area of the latter is much larger than the usual scale of variability (e.g. in terms of correlation lengths) of the observed precipitation field. In other words: does the internal structure of the rainfall process within each pixel seriously affect the non-linear transformation of precipitation into radiances and vice versa ? The question holds practical implications in the use of passive microwave techniques for the monitoring of space–time rainfall: a correct answer is urgently needed for improving the reliability of downscaling models for the extremes.

3.2. PASSIVE MICROWAVE TECHNIQUES

The potential of using passive microwave radiometry in rainfall monitoring is strictly related to the responsivity of the up-welling radiation – observed at the top of the clouds – to the micro-physics of precipitation. Details about this issue are discussed later in the following together with the identification of the available rainfall retrieval algorithms while a deeper insight can be found in Kidd and Barrett [7], Mugnai and Smith [14] and Smith and Mugnai [19]. The important point here is that the microwave regime – up welling from the earth/atmosphere system – is characterized by very low energy, requiring that a large field of view is provided by the orbiting sensor in order to ensure sufficient signal intensities when compared to the background noise of the instrument [20]. On the other hand the main advantage of exploiting the remote sensing of the earth characteristics and atmospheric phenomena lies in the opportunity of obtaining a comprehensive view of the large resolution dynamics, on a scale which is directly dependent on the altitude of the satellite orbit. This is in evident conflict with the need for enhanced accuracy in rainfall estimation which is a function of the spatial resolution of the sensor.

Evaluating the bias due to the use of satellite information derived from a large sampling scale is not of negligible importance when different scales are used simultaneously, as in the case of the multifrequency rainfall retrieval process. In this perspective the well-known beam-filling problem is defined as the difficulty of relating the microwave radiation – received by the sensor from a 'source field' of a distributed physical variable and up welling through the atmosphere – to the actual average of that variable within the FOV. The small scale variability of the precipitation field, as well as the internal correlation structure of rainfall, must be compared to the scale of the footprint of the sensor in order to address the beam-filling problem in the limits of any brightness–temperature/rain-rate retrieval procedure. A clear formulation of this concept in the case of precipitation monitoring is obtained by defining the average rainfall rate within the FOV of the sensor as:

$$R_{\mathrm{FOV}} = (1/A_{\mathrm{FOV}}) \cdot \int_{A_{\mathrm{FOV}}} r(x,t)\,\mathrm{d}A$$

where A_{FOV} is the area of the field of view at a given frequency and $r(x,t)$ is the rainfall rate at location x and time t. Let us define the up welling radiation received by the sensor within the FOV as:

$$I_{\mathrm{FOV}} = (1/A_{\mathrm{FOV}}) \cdot \int_{A_{\mathrm{FOV}}} i(x,t)\,\mathrm{d}A$$

where $i(x,t)$ represents the radiation intensity produced at point x. It should be noted that, in the last expression, $i(x,t)$ is not only a function of the corresponding point value of the rainfall rate $r(x,t)$ but also of the columnar structure of the cloud over that point and of some background noise which adds a 'random' component to the measurement. In this context the beam-filling problem can be defined as the problem of relating R_{FOV} to I_{FOV} – which is measured – when the relationship between $r(x,t)$ and $i(x,t)$ presents strong non-linear components.

The even complex relationship which is assumed to hold between I_{FOV} and the average rainfall R_{FOV} in order to develop suitable rainfall retrieval algorithms actually preserves a one-to-one relationship between the brightness temperatures and rainfall rates which is acceptable only when the dimension of the FOV is small enough as to make the effect of the internal rainfall variability negligible against the average behavior. Otherwise the up welling radiation I_{FOV} is a function of A_{FOV} as well as of the variance, correlation length and intermittence (percentage of no-rain areas) of the precipitation field. The analysis of such a relationship is the major unresolved task to be addressed in order to assess the actual reliability of the traditionally available brightness temperature-rain rate retrieval algorithms.

3.3. FROM OBSERVABLES TO PROCESSES

The development of either a theoretical or empirical relationship between passive microwave measurements and precipitation intensities at the ground has been addressed in the literature on the basis of different approaches [21], [16]. The simplest one consists of determining some statistical radiance-precipitation relationship by just comparing a set of coupled remotely sensed and ground-based observations not involving at all any cloud micro-physics analysis. As already pointed out by several authors [15], brightness temperatures appear to be more realistically responsive to the micro-physical structure of the middle and upper layers of the precipitating cloud system and this relationship has to be investigated in order to alleviate the uncertainties of the indirect estimation.

A suitable procedure must take into account the fact that different microwave measurements based on different frequencies are sensitive to different layers of the cloud system: the mentioned SSM/I scanning frequencies are associated with the middle and upper cloud layers, the higher frequencies being less penetrating into the micro-physics of the cloud system. The use of simultaneous data collected at different frequencies has thus the potential of providing the best estimate of the composition of the cloud layers.

A different approach is based on the use of some radiative transfer model together with the synthetic generation of a set of possible cloud structure scenarios in order to relate an emerging radiance to the rain rates produced by the cloud development model. The need for the implementation of realistic cloud simulators is suggested to introduce a class of hybrid statistical–physical algorithms, whose advantages and features are described in detail by Mugna *et al.* [16]. The use of a more detailed micro-physical model leads to higher reliability but, in the mean time, demands that the non-uniqueness of the relationship between the rain rate and brightness temperature – as produced by a more detailed microphysical dataset – be resolved by using an inversion type algorithm instead of a regression one. In order to best exploit the information from the satellite measurement, a pre-processing of data at different frequencies has to be carried out so as to obtain a homogeneous sample size.

Actually, from the hydrological point of view, the influence of the observed variability of the rain field within the sensor footprint in the face of satellite measurements of the up welling radiances should be investigated in detail. Two main questions arise in this context:

- are the two different precipitation fields characterized by the same internal structure (i.e. intermittence and spatial auto correlation) and by the same statistical parameters (i.e. mean value and variance) at least really equivalent in terms of up-welling radiances, in the sense that it is not possible to distinguish them in the satellite images ?
- what is the influence of the variation of any single structure parameter and of the variance on the brightness temperatures measured on the scale of the FOV of the sensor?

Answering these questions is equivalent to validating the reliability of passive microwave rainfall estimates from satellite sensors against the variability and internal features of the observed rainfall field. This is not however the scope of the present paper which just aims at describing the outline of a suitable hydrological approach for dealing with the problem outlined. A possible approach is indeed that of developing the inversion of the described retrieval algorithms, i.e., we could say, to switching to a hydrological perspective. In summary, the philosophy of the available retrieval algorithms is based on the generation of the cloud micro-physical data set and then on the derivation of the corresponding couples of emerging radiances and related rainfall rates on the ground. A statistical inversion of the radiation sub model allows the derivation of the most probable cloud micro-physics scenario, given the observed up welling radiance, and then the rainfall as a homogeneous mean value all over the footprint area. The hydrological approach, accounting for the small scale characteristics of the rainfall field, should be based on the inversion of that branch of the algorithm which deals with the rainfall/cloud structure relationship, i.e. the gravity fallout model. Two different theoretical ways are proposed here for use in future work:

- the use of the rainfall data set as obtained from the three-dimensional microphysical model by classifying it on the basis of the internal structure and randomness parameters and the application of statistical inversion in order to obtain the corresponding cloud structure;
- the generation of reliable synthetic rainfall fields with given structure and randomness characteristics [8], [9] for performing the analysis of the system on a smaller scale, the latter being the best compromise between the two opposite constraints of being small enough as to keep the beam filling problem negligible and large enough to allow proper application of the involved atmospheric models.

In this way the cloud structure data set is realized on the basis of the produced rainfall fields, the latter being characterized not only by the mean value over the sensor FOV, but also by the known internal variability and structure characteristics. By using the radiation transfer model on this data set a deeper understanding of the potential information contained in passive multi-frequency remote sensing measurements will be gained together with a more satisfactory validation of such measurements on the scale required by most of the hydrological applications.

4. Conclusions and Perspectives for Flood Hazard Assessment

The problem of the assessment and forecasting of hydrometeorological hazards within the Mediterranean area needs an urgent change in traditional investigation and monitoring perspectives in order to allow for a deeper understanding of both meteorological and hydrological processes which evolve over different spatial and temporal scales. It is now widely recognized [11] that traditional warning systems, relying on ground-based rainfall observations and rainfall-runoff modeling procedures alone, are fairly inadequate to provide accurate predictions within any suitable lead time. Quite a large interdisciplinary research effort has thus been dedicated by hydrologists, meteorologists and remote sensing scientists towards the development of operational tools able to fulfil the requirements of flood hazard assessment and forecasting within the Mediterranean region [17], [11], [18], [12]. The operational feasibility of flash flood forecasting in the Mediterranean area requires the development and the validation of methodologies suitable to predict both the ground effects of extreme storms and the response of the social environment to an early warning message as well. In fact, significant lead time constraints arise from the capability of social organizations to institute and carry out precautionary measures: large urban settlements need many hours to put into operation suitable safeguards for schools, museums, and public buildings, as well as for the diffusion of information to the population. A shorter lead time is required only for special or technological installations. Usually the lead time required by the social environment exceeds the hydrological response time of the catchments of concern: hydrometric warning is feasible only for major rivers. In most cases not only discharge but rainfall has to be predicted up to a certain degree of confidence so that Quantitative Precipitation Forecasting (QPF) becomes the crucial issue.

Integrated multisensor systems afford some promise of joining different monitoring resolutions and different interpretation techniques into an operational procedure able to complement the remotely sensed perception of the large scale dynamics of cloud aggregates with the assessment – at least in a stochastic framework – of the small scale variability of the precipitation field on the ground. The strong limitation in making extensive use of remote sensing techniques in flood forecasting is mainly due to the fact that the available sensors do not measure rainfall directly. As already discussed, the reliability of this kind of measurement in the face of the rainfall process on the ground is still far from being satisfactorily tested. The use of rainfall retrieval algorithms based on passive microwave imagery is not very useful in this context, at least at the present stage of the associated operational capabilities. Though much more directly linked to the inner micro-physics of the observed cloud system, with respect to the infrared imagery, the information is provided at an even coarser spatial resolution. Moreover, the timing of the polar satellite passages (once or twice per day) makes the information rather unsuitable, at present, for real time flood forecasting applications. However, passive microwave imagery does play a role in that:

- it is useful to 'validate' rainfall rates as detected for potentially hazardous cloud systems against the information obtained, at some coarser aggregation scale, by some more physically based estimation technique – at least when the latter is available according to the satellite passages;

- it is likely that integration techniques making use of calibration efforts already undertaken in the case of past events would greatly enhance the accuracy of storm identification techniques based on IR images alone (i.e. the tracking procedure described in this paper).

Once MCCs are identified, they must be tracked along their space–time evolution and predicted, in terms of location, extension, intensity, etc. for the subsequent time steps. A possible approach to flood forecasting in the case of small size catchments is that of using the available information about the observed and predicted convective cloud coverage, as derived from the observations at the larger scale, in order to produce estimates of the probability of occurrence of heavy rainfall events within the framework of automatic procedures for the analysis of flood hazard at the regional scale as developed by Lanza and Siccardi [10]. The approach is based on the stochastic simulation of space–time rainfall fields conditional to the observations. It has been shown [9] that a suitable procedure can be applied in order to synthetically derive a random field representing a possible realization of the precipitation process on the basis of the estimation of the statistical parameters obtained through the available monitoring devices.

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