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Geographical perspectives of space, time, and scale

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'... We usually opt for one level of analysis exclusively, without considering the range of other alternatives. To judge from the literature this choice is a private act of faith, not to be reported publically.'

Mary Watson 1978

1. Introduction

In the discipline of geography, scale has always been a major issue; however, geographers do not seem to explicitly state their scales of analysis any more fully than scientists in other disciplines. Nevertheless, the geographic literature is rich in philosophical discussions of spatial scales and methodological solutions for dealing with scale (*e.g.*, Harvey 1969). These solutions should not need to be reinvented as the ecologic and biological sciences attempt to more fully incorporate the spatial dimension into their work and to move to ever broader-scales of spatial analysis.

This chapter reviews the major scale issues in geography and the manner in which spatial scale problems have been manipulated and resolved. In particular I discuss examples of the nature of the variables used in spatial/regional models at various scales, the methodological dilemmas and inferential fallacies encountered in spatial analyses, and some common solutions. In addition I examine the basis for selection of scales (including time scales) and some of the trade-offs or concessions needed to move to analyses at broader continental and global scales. Finally, as part of my conclusions, a case is made for a fuller incorporation of space and spatial scales into hierarchy theory.

First I must admit that I am a geographer, specifically a physical geographer, and that this essay fully reflects my biases. I review the literature in human and economic geography, climatology, geomorphology, and remote sensing, which are often a part of the discipline as well as literature in related disciplines of landscape ecology, ecology, and meteorology.

Geography has often been criticized for its breadth of topics and divergent points of view (Hart 1982). The discipline spans human, biological, and physical environmental arenas and includes spatial scales from a single point to the entire globe. It follows then, that geography has abundant literature on methodologies and the merits of various research agendas. Problems in the search for causality and the predictions of spatial patterns are often discussed (Harvey 1969). It is interesting, however, that the question of whether one is working at a 'fundamental' level is never discussed in geography.

Remarkably, the common bond of the spatial point of view seems to cement the discipline (Clark *et al.* 1987). This finding leads to the question: what ingredients differentiate a study as geographic or spatial? It seems that when one or more spatial variables are explicit, distinct variables in an analysis, the study becomes a spatial analysis (Meentemeyer and Box 1987). Examples of spatial variables include area, range, distance, direction, spatial geometries and patterns, spatial connectivity, isolation, diffusion, spatial associations, and scale (Abler *et al.* 1971). These variables may be considered 'geographic primitives' (Mitchelson unpublished).

Watson (1978) maintains that '... scale is a 'geographic' variable almost as sacred as distance.' Perhaps cartography is the geographic subdiscipline that is most adept at handling spatial scale. Well-developed rules have been developed to balance the scale versus resolution-information content of a map (Board 1967). One of the first decisions is selection of a map scale; indeed creative selection of map scales may be part of the art in cartography. Very likely it is the geographer's affinity with mapmaking that makes scale 'sacred,' but that does not mean that scales are always stated explicitly. Nor is scale for most researchers simply a question of balancing the size (extent) of a region with desired levels of resolution. One's purpose and philosophical viewpoint toward space has much to do with the nature of research designs and results.

2. Absolute versus relative space

It is necessary in my view to recognize *a priori* whether a study involves absolute or relative space. Harvey (1969) presents an excellent review of the evolution of these two points of view. He points out that Kant had a great influence on geography but that Kant expressed in his latter works an absolute view of space, (*i.e.*, space may exist for its own sake independent of matter). Accordingly, space just 'is,' and it may therefore be viewed as a 'container' for elements of the earth's surface (Table 1). In other words, the job of geography should consist mainly of filling the 'container' with information. Absolute scale involves primarily an Euclidian point of view usually based on a defined grid system. The location of elements within the grid of the

Table 1. Philosophical views of space: the difference between absolute and relative space.

Absolute space	Relative space
Space can exist independent of any matter	Space exists only with reference to things and processes
Space as a 'container'	Space is defined by things and processes
Associated primarily with inventory and mapping	Associated primarily with studies of forms, patterns, functions, rates, diffusion
Euclidean space	May involve non-Euclidean (transformed) space

region under consideration is critical, as is the size (scale) of the region. This is the point of view of conventional cartography, remote sensing, and the mapping sciences. It is the appropriate approach in inventory, planning, and most mapping and descriptive studies. Moreover, it is quite easy to view 'subcontainers' within a 'container' and to devise appropriate classification schemes. A city may be viewed as having several districts, areas, or neighborhoods, all of which may show ever-smaller areal units. Depending on the classification scheme and skills of discrimination, the creation of spatial hierarchies is quite straightforward, albeit in absolute space.

The relativistic point of view involves two considerations. First of all, space is defined by the spatial elements and processes under consideration. The 'relevant' space is defined by the spatial processes, *e.g.*, migration and commuting patterns, watersheds, dispersion of pollutants, and even the diffusion of ideas and information. In studies of the relationship between (among) spatial patterns/forms and functions, processes and rates often define the scales and regions. Secondly this approach may result in space being defined in non-Euclidean terms. Even distance may be relative (Harvey 1969). Two areas separated by a barrier may be close in absolute space and very distant in relative space when time, rates, and interactions are considered. Thus a functional (spatial process) region may be difficult to map in terms of absolute space.

The need for more broad-scale studies generated by the International Geosphere-Biosphere Program (IGBP) has often produced calls for the use of advanced techniques in remote sensing and applications of geographic information systems (GISs) (*e.g.*, NASA 1986; Kotlyakov *et al.* 1988). Some problems can realistically be solved only by these techniques; however, they involve absolute space almost exclusively.

Most modern work in geography involves a relative view of space (Harvey 1969; Abler *et al.* 1971) because much of this work involves spatial processes and mechanisms. Both absolute and relative space involve scale, but each approach tends to produce distinctly different research results. Moreover the nature of the resulting models is influenced by scale, especially for spatial models produced from the relativistic point of view. However, this fact leads to the additional complication that spatial scales need not be viewed only in absolute terms. Scale is also relative when scales change across a map. It is instructive to examine changes in model structures and relevant variables in the geographic (broadly defined) literature caused by changes in spatial scales.

3. Variables changing with scale

As in many other disciplines, geography has debated the appropriate scale of analysis for various processes (Nir 1987). There is, however, widespread agreement that changes in scale change the important, relevant variables. Moreover the value of a phenomenon at a particular place is usually driven by causal processes which operate at differing scales (Mitchelson unpublished). In studies of human migration, the models for predicting the spatial patterns of intrastate movement usually involve regionally aggregated data for groups. Often included are variables related to labor demand, investment and business climate, and income, *i.e.*, group and 'structural-contextual' variables. Intraurban migration models often involve the age, education, and income of individuals, as well as kinship and other affinity measures. Distance and status may also be useful measures, but at this scale most variables delimit the individual (Pandit, personal communication.

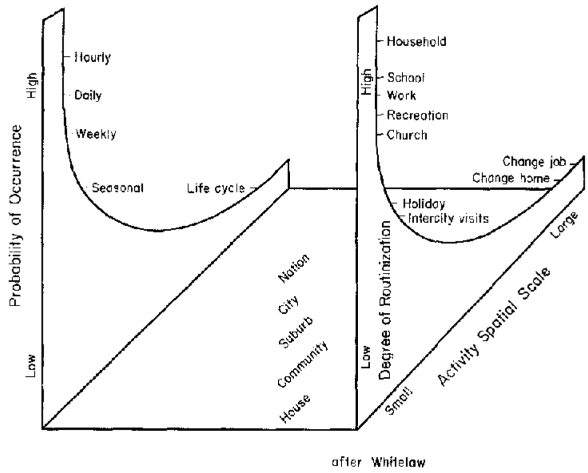

Fig. 1. The activity space of individuals as it relates to time involved, distance travelled, degree of routinization, and probability of occurrence.

In planning and modeling of water supply networks for third-world countries, studies at a national scale often involve urban and regional water demands. At a village scale, walking time and distance to a spigot may be preeminent concerns (Logan, personal communication). In other words, group and regional aggregation variables are replaced by measures of the individual person or family.

Behavioral geography is a subdiscipline in geography which examines the use of space by individuals and the timing of this use. Portions of this discipline have been termed activity space and time-space geography (Carlstein and Thrift 1978). The approaches taken have shown that human activities which are the most routine involve the smallest spaces and are correlated with the shortest periods of time (Fig. 1). Rare, unroutine activities often involve movement over large spaces or distances and can be so rare as to recur only a few times (or once) in a lifetime (*e.g.*, changing careers). The most frequent movements are of the shortest distance and may also display effort-minimization principles (Zipf 1949, Holley 1978). Thus different spatial activities have radically different time and space scales. Perhaps it is now time to incorporate spatial activities of nonhuman entities into this framework.

Table 2. The correspondence among time scales, scales of atmospheric variables and topographic variables most frequently used in studies of orographic precipitation.

	Variables	
Time	Atmospheric	Topographic
Minute	Local convection Dew point depression	Slope %
Hour	Feeder cloud Potential instability Wind speed	Orientation Elevation
Day	Synoptic events Vorticity Short-wave patterns	Exposure?
Year	Precipitable H_2O Upper-level divergence Baroclinic zones SST and ENSO	Elevation Exposure Slope % Orientation
Normals	Baroclinic zones Long wave patterns Wind persistence and direction Wind speed	Exposure Orientation

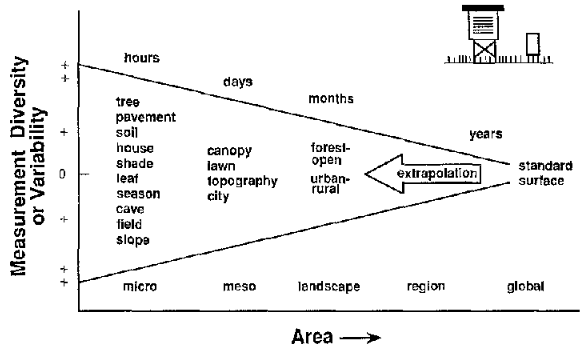

Fig. 2. Time and spatial area relationships with measurement diversity in physical climatology.

3.1. Studies in orographic precipitation

It is also possible to review the research literature on a particular phenomenon with a view to the time and space scales which have been used. Presumably a sufficient number of studies across a sufficient diversity of spatial scales have been conducted, and some indication of the changes in relevant variables should be evident. I have done this for studies of precipitation patterns in mountainous areas (Table 2). For precipitation events at a point (weather station) lasting for minutes to perhaps an hour, the studies are highly process oriented and often involve atmospheric variables defining local convection and dew point depression. The actual topography itself does not seem especially important, although percentage slope is sometimes considered.

At the time scale of an hour or more, the formation of feeder clouds at low levels, potential instability, and current windspeeds are often examined. As the time scale lengthens, the appropriate atmospheric variables involve even broader scales (Table 2). The topographic variables used show less-well-defined relationships with scale. Spatial scales are poorly defined in many studies, and studies at contintental and global scales are nonexistent (Basist 1989). Probably the interactions of elevation with exposure and of slope with orientation are more appropriate at broad regional scales; surprisingly, elevation alone is a less-useful predictor than other measures of topography (Basist 1989).

3.2. Studies in physical climatology

It has been argued elsewhere (Meentemeyer and Box 1987) that processes and phenomena which involve broad spatial scales appear to be changing so slowly that very long time scales are needed to observe and model these entities. The literature of the physical climatology of the earth's surface is also illustrative of the pragmatic problem of matching time and space scales (Flohn 1981), as well as the nature of the variables which appear important. At the scales of micrometeorology, measurements are rarely conducted for more than a few hours or days; however, the variety of situations and the number of environmental variables studied have been exceptionally large (Fig. 2).

Nearly every conceivable location and environmental variable (including factors such as temperature, moisture, radiation, wind, and heat flux) has been monitored. As measurement time scales are lengthened, the areas become more aggregated and

Table 3. Some observations and speculations on spatial scale.

1. Broad-scale patterns (aggregate scales) generate hypotheses; fine scales (individual level) determine cause and effect (Watson 1978).
2. Sciences dealing mostly with processes, *e.g.*, meteorology are better able to switch scales (Steyn *et al.* 1981).
3. Sciences dealing mostly with phenomenon have more difficulty with time and space scales (*e.g.*, geography, climatology, landscape ecology) because the size of the phenomenon decides the scale.
4. As the spatial scale becomes finer (smaller spatial units) the vertical three-dimensional aspect becomes more important.
5. Meso scales are usually the most difficult to define and model.

defined by terms such as slope, city versus rural, and land versus water. The variety of earth surface 'classes' becomes more restricted, as well as the number of environmental variables measured continuously. In addition, the three-dimensional spaces of microclimatology, in which the vertical dimension defined by the boundary layer is significant, are progressively collapsed to a standard two-dimensional surface at broader scales (Table 3). The vast majority of long-term measurements are made only at standard weather stations, where by international agreement measurements are made in the same manner over most of the globe.

Such standard or reference stations at which long-term measurements are made are so expensive to maintain that only governments have sufficient resources. It should be mentioned, however, that these stations were not designed to answer questions about biotic-abiotic interactions or even about climate change but for meteorologists producing weather forecasts (Mather 1974), justifying the expense of their operation. Yet it is these point measurements which have been used to interpolate, extrapolate, and describe abiotic environments across the diverse elements of landscapes, regions, and the entire globe. In fact, there is a clear trend in the literature of physical climatology to extrapolate from coarser to finer spatial and time scales – rarely in the opposite direction. Unfortunately, weather stations are biased toward low-elevation areas, regions near higher-population densities, and land masses. Even this very rich data source is not 'global.'

3.3. Scale thresholds?

Reviews of research literature on narrowly defined phenomena should be conducted in a systematic way to find additional order in the effects of changes in scale. Some phenomena show distinct scale thresholds. In geomorphology/hydrology, small watersheds in temperate zones display a very peaked discharge response. At about 300 km^2, the peak flattens because at this size many watersheds support floodplains (Klein 1976, in Beven *et al.* 1988).

The search for changes in model structures and even thresholds in spatial systems can fruitfully be started now. Moreover, it is likely that research in broad-scale spatial phenomena and processes will proliferate. Unfortunately spatial analyses and varying scales of time-space resolution can produce some difficult methodological problems.

4. Methodological dilemmas in spatial analyses

Tobler (1969) stated the problem of spatial autocorrelation succinctly in his first law of geography: near things are more related than distant things. Thus every spatial element may be correlated, *i.e.*, it is similar to its neighboring element. Without spatial autocorrelation, however, the surface of the earth would appear entirely random. Spatial autocorrelation is, in fact, the basis for the recognition of spatial variability, of land versus water, field versus forest, high density versus low density, etc. Often it is useful to search for the level of resolution which maximizes the spatial variability of a phenomenon (Harvey 1969). This is then the level at which spatial patterns may be most easily recognized and studied. The underpinnings of spatial autocorrelation are treated elsewhere (*e.g.*, Cliff and Ord 1973).

Although spatial autocorrelation has received much recent attention, especially by soil scientists (*e.g.*, Kachanoski 1988), it is one of the more esoteric methodological problems in spatial analyses. Perhaps the two most important problems in geographic research are the lack of experimental control and the size of the observational unit. It is safe to say that nearly every geographic primitive (area, shape, distance, scale, etc.) needs to be controlled for if the results (models?) are to be general and transferable to other settings. The dependency of results on the size of the spatial unit in an analysis provides ample examples of potentially erroneous inferences.

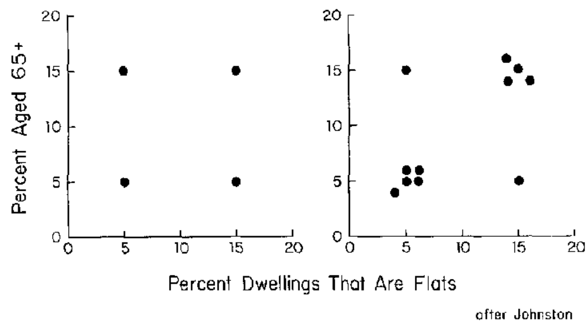

Fig. 3. An influence of the size of a spatial observation on spatial correlations.

4.1. Erroneous inferences

Generalizations across spatial scales and units of aggregation have generated three types of erroneous inference (Mitchelson, unpublished): (a) individualistic fallacy – imputing macrolevel (aggregate) relationships from microlevel (individualistic) relationships, (b) cross-level fallacies – making inferences from one subpopulation to another at the same level of analysis, and (c) ecological fallacy – making inferences from higher levels of aggregation to a lower level.

In geography, when spatial units (patches, districts, areas, regions, gaps) are the elements of a correlation-regression analysis, the results are termed 'ecological correlation' (Robinson 1950). Generally, when the size of the observational unit, is large, the estimate of variation for the phenomenon is low because the means vary less than the values upon which they are based. This can lead to an erroneous inference termed the 'ecological fallacy' in economic geography, *i.e.*, making inferences about the individual or lower levels from the higher levels of aggregation. Robinson (1950) demonstrated 'ecological fallacy' in the correlation between race and measured IQ. When the United States was divided into nine regions, the correlation coefficient was 0.946 ($r^2 = 0.89$), and a value of 0.733 ($r^2 = 0.537$) at the level of 48 states (regions). However, at the individual level, the coefficients were only $r = 0.203$ ($r^2 = 0.04$). Good statistical designs can, however, overcome this potential fallacy.

Johnston (1976) provides an extremely simple example of the problem of unit size, autocorrelation, and 'ecological fallacy' (Fig. 3). The diagram on the left represents a plot of the relationship between people aged 65 and over and the percentage of dwellings that are flats in each of four areas in London. The correlation coefficient is zero. Two regions are large, however, and when broken down into equal-sized census tracts (right-hand figure), the correlation coefficient is about 0.6 (Johnston 1976).

A particularly demanding methodological problem in geography has been inference of spatial process from spatial form. Indeed, it is from spatial form that most processes are 'discovered.' Unfortunately empirical results are usually scale specific. Patterns which appear to be ordered at one scale may appear random at other scales (Miller 1978). Moreover, different spatial processes can generate exactly the same spatial patterns. Often fine-scale processes can cause clumping patterns, but the clumps show the results of processes leading to as much dispersion as possible. For example, shoe stores tend to clump to increase comparative shopping, but each clump desires to be as far as possible from another clump of shoe stores.

The size of the observational unit may also influence statistical distributions. Generally Poisson distributions are generated from small sampling quadrats, and large quadrats generate negative binomial distributions (Watson 1978). This can influence inference (process from form) as well as spatial correlation.

The rules for optimal spatial sampling and data grouping to reduce the loss of information on individuals have been developed (*e.g.*, Clark and Avery 1976), and these rules can reduce some common fallacies in inference. Missing spatial data can, however, produce special problems. If the goal is a

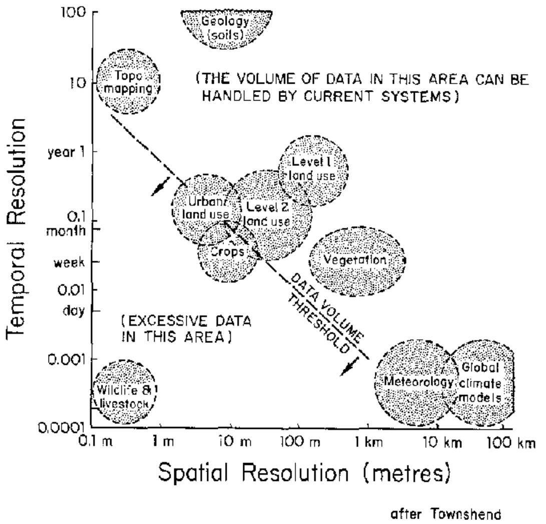

Fig. 4. The influence of levels of temporal and spatial resolution on data-handling thresholds for various phenomena.

map of a process or phenomenon, or if a model is the goal, then missing data are a serious problem. Does one interpolate, extrapolate, or produce other estimates of values for missing spaces? Certainly spatial averaging is possible, and it is also possible to fit trend surfaces of varying complexity. Unfortunately these approaches are also scale dependent and therefore scales must be considered in estimating missing data.

4.2. Coupling hierarchical levels

One solution to poor spatial data coverage is the development of a model of spatial relationships that couples two hierarchical levels. Watson (1978) notes, however, that few studies in geography have combined macrospatial and microspatial levels of analysis because of the incredibly large amounts of data needed. Indeed many scale problems seem in actuality to involve thresholds in data-handling abilities. Figure 4, based on Townsend (1987), demonstrates the boundary between scales which produce 'excessive' data and data volumes which can be handled by current systems in remote sensing, GISs, and atmospheric circulation models. The constraints may be caused by any combination of hardware, software, or model structure. Naturally, the detection of spatial processes and phenomena which display great temporal variability and require high levels of resolution produce excessive volumes of data. Thus for some fine-scaled phenomenon, simple extrapolation might be acceptably accurate but meet data-handling thresholds. Furthermore, multiple time or space scales would push the data volume threshold to the upper right-hand portion of Fig. 4.

Hierarchical coupling is common in applied climatology as is extrapolation from broad to fine scales. Climatology was in its infancy a weak step-sister of meteorology (Mather 1974). The data collected by meteorologists in their attempts to forecast the weather were the basis of the discipline. At various spatial scales, it seems natural then to correlate these temperature and precipitation records with ecosystem processes. Unfortunately, temperature and precipitation are measures of the state of the atmosphere and may not represent well that part of climate which is actually entering into an environmental process. It is necessary to conceive an 'effective climate' (term coined by D.B. Carter): that climate or abiotic environment most intimately involved in an environmental process. For some processes, for example, soil temperature may be more 'effective' than air temperature and soil moisture more so than precipitation. In the terminology of hierarchy theory (O'Neill *et al.* 1986; O'Neill 1988; Salthe 1985), this appropriate climatic (abiotic) environment could be considered the 'constraints' on lower levels. I suggest that these constraints must be the effective climate, the environment closest to the actual processes, and not just weather records.

4.3. The data-rich to data-poor solution

Sometimes available data determine research designs and space-time scales. This may be especially true for broad-scale geographical-ecological problems of the type proposed as part of IGBP. Geographers and climatologists have coupled hierarchical levels with success when the higher level (constraints) have been data-rich. In fact, many spatial models are based on the concept of predicting the spatial patterns of data-poor (especially involving poor spatial coverage and missing data) phenomena and processes on the basis of data-rich constraint variables. My own work has involved predicting the geography of litter decomposition rates at continental scales on the basis of abiotic (climatic) constraints (Meentemeyer 1984). In most of these spatial models, the climatic variables have not been precipitation and air temperature, but instead have been evapotranspiration and measures of seasonality, which apparently enter more effectively into decomposer systems. These models have been criticized for not including fully the organismic, chemical and physical variables well known to control decay rates. However, adding such information produces exceedingly complex models, which when coupled with the driving variables of climate, do very little to improve the prediction of broad-scale geographic patterns. Apparently a threshold is reached at which the 'costs' of additional causal or mechanistic information is not balanced by improved predictions of spatial patterns. At this point information on the lower levels cannot simply be moved upscale.

Fortunately we already have many of the data-rich variables at near global scales which can be used as the driving variables in predicting spatial patterns at the broader scales. Information on climate, soil, topography, vegetation, and land use comes readily to mind. Remote sensing has produced spatial coverage for additional variables, especially for the oceans (Walsh and Dieterle 1988). Perhaps the innovative spatial-environmental models of the future will involve higher- to lower-level couplings to produce new geographies of processes and their rates which cannot now be mapped.

As shown above, in Fig. 2, and in the hierarchy literature, extrapolation from higher to lower levels has been successful, with much less success for fine-to-broad extrapolations. The challenge for the global climate change program then is exceedingly difficult because it involves analysis of the levels and constraints which are above that of some of our most useful and data-rich constraints (*e.g.*, weather records). To improve the spatial modeling component in landscape ecology, it may be helpful to find the appropriate constraints for the spatial hierarchical level of concern.

4.4. Loss of detail in spatial analysis

The selection of spatial scales involves much more than selection of levels of spatial resolution. Nevertheless it should be clear that the addition of the spatial dimension in the study of nearly any process or phenomenon may involve a variety of trade-offs. Models for broader-scale patterns result in less predictive accuracy at specific points or places. Since geography is primarily an empirical science, the generalizations (models) are only as good as the finest-grain spatial data available. Often it is necessary to sample for just one or two variables at many points (regions, places, etc.) in order to develop good spatial data sets. The details of entities and processes at places often cannot be used. Thus the model may appear to be 'superficial,' but, without the sacrifice in detail, a spatial model and/or a predictive map would not have been possible.

The incorporation of the spatial dimension in landscape ecology and projects under the global change programs require the substitution of more samples geographically but sampling of less detail at each site or place. It seems that the addition of the spatial dimension forces attention to higher hierarchical levels: the broader the scale, the higher the level.

The history of spatial modeling has shown the success of modeling on the basis of higher-level constraints. Lower levels provide data for testing of hypotheses and the search for causality (Table 3). Therefore it is apparent that much of the cherished detail of the reductionist sciences may not be needed, and indeed cannot be used, in broad-scale spatial modeling.

5. How spatial scales are selected (apparently)

Steyn *et al.* (1981) make the interesting point that disciplines concerned primarily with processes, such as meteorology, are able to switch scales with relative ease (*e.g.*, Gedgelman 1985). On the other hand, disciplines dealing with phenomenon are often restricted by the size of the phenomenon (Table 4). Many phenomena come in characteristic

Table 4. The selection of spatial scales: some apparent determinants and constraints.

1. The size and 'speed' of a spatial phenomenon or process
2. Existing maps and map scales
3. Scales of aerial photography and remote sensing images
4. Size of the spatial units (*e.g.*, quadrat, tract, patch, area, gap)
5. Mathematical-statistical constraints (*e.g.*, spatial-temporal autocorrelation, centrality bias, missing data)
6. Within-site versus across-site variability
7. Data handling thresholds
   A. Time
   B. Technology
   C. Money
8. Practical-empirical considerations
9. Philosophical propensities (*e.g.*, micro versus macro, absolute space versus relative space)
10. Arbitrary

size classes. Moreover phenomena associated with ephemeral processes or fast relaxation times may need to be studied at fine time-space scales (Table 4).

The tremendous burden of sampling spatial variables adequately often means that existing data sources and map scales (*e.g.*, 1:24,000, 1:50,000) must be used. Thus it is common to define the spatial scale of a study by the approximate corresponding map scales (*e.g.*, Krummel *et al.* 1987). Similarly the scales of aerial photography and remote sensing images may constrain the spatial scales chosen. The size of quadrats, census tracts, patches, and even pixel size may fix the limits of suitable scales.

Mathematical and statistical considerations may affect the selection of scales. Spatial and temporal autocorrelation for phenomena and processes may vary with scale, depending on the degree of spatial and temporal heterogeneity. In essence the scales need to match the heterogeneity; *i.e.*, the phenomenon dictates the scale (*e.g.*, White 1987). Some techniques, such as those based on nearest-neighbor analyses, have a centrality bias which changes with scale. Studies of spatial interaction are especially sensitive to scale. Larger regions tend to incorporate more potential interactions and have a larger centrality bias, depending on the nature of the interactions. Similarly, scale may be determined by the degree of within-site versus across-site variability. Generally the scale selected is the one which maximizes across-site variability (Table 4).

Data-handling thresholds are intertwined with time and space scales. This data-handling threshold has been moved to higher time-space resolution by technology. However, time and money constraints often seem to limit spatial scales, the number of variables considered, and the number of hierarchical level used.

The abundant arguments in geography regarding the merits of microscale versus macroscale analyses and of all scales in between point to basic differences in philosophical stances on scale. Researchers with similar propensities select similar scales and seem therefore to group together. Perhaps this is caused by dominant paradigms, data sources, and other realities. Is it thus possible to categorize disciplines, subdisciplines, and groups on the basis of their 'favorite' time and space scales? In the end it seems that scales are unconsciously selected and therefore may seem to be entirely *arbitrary*.

6. Summary and conclusions

This article reviews space and time scales from a geographer's point of view. Because spatial phenomena come in incredibly different size classes, geographers have conducted analyses across many orders of spatial magnitude. Geographers seem adept at moving from one scale to another, but they are not prone to explicitly state these scales *a priori*. Moreover, in spite of many appeals for multiscaler research (*e.g.*, Abler 1987; Miller 1970; Stone 1968; Kirkby 1985), this is seldom done, although higher-level information is often used to predict lower levels. Good multiscale work apparently meets data-handling thresholds rather quickly.

Most geographic research is now conducted with a relativistic view of space rather than a view of space as a 'container.' Spatial scales for relative space are more difficult to define, however, than those for the absolute space of cartography and remote sensing.

The relevant, important, and useful variables from a modeling standpoint change with spatial scale. By reviewing the literature on a topic in a systematic way, as was done here for physical climatology and orographic precipitation, this scale change in variables can be seen. We do not as yet have models of the changes in models caused by changes in scale.

Spatial data violate nearly every requirement for parametric statistical analysis (Meentemeyer and Box 1987), which is partially responsible for fallacies and erroneous inference. Many of these problems are scale dependent. Based on the work of Harvey (1969), we see that there are three primary methodological problems in spatial analyses. There are first of all the differences in inference and relevant variables caused by different scales or hierarchical levels. This has been called the 'scale problem' in geographic literature. Secondly, the description and modeling of spatial patterns, as noted above, may defy easy solutions, and finally the relationships between spatial patterns and process remain a challenge.

The geographic literature contains many examples of extrapolations to lower levels from higher levels. Often the higher levels have been more widely sampled geographically (*e.g.*, weather and climate, topography) and may be data rich. Models which predict spatial patterns and process often use the data-rich higher levels as driving variables for lower levels. Young (1978) argues that central place theory in geography should be a component of hierarchy theory. Indeed it can be argued here that space is inherently hierarchical and needs to be more fully incorporated into hierarchy theory.

As the various disciplines under the umbrella of the environmental sciences more fully incorporate the spatial dimension into their research agendas, problems associated with spatial scale will be encountered. Many of these problems have in varying degrees been recognized if not solved. Nevertheless it is worth noting Clark's (1985) warning, 'No simple rules can automatically select the "proper" scale for attention.'

Good geographic models require good geographic coverage, but this may mean that lower-level details are simply not needed. As mentioned earlier, the question of whether one is working at a 'fundamental' level is never discussed in geography. The Long-Term Ecological Reserve (LTER) sites are a step in the right direction, but a geographer would prefer much more intensive spatial sampling, even if that means a sacrifice in accuracy or detail. Otherwise a spatial analysis may not be possible. It remains to be seen to what degree the reductionist sciences can contribute to IGBP. More work with explicitly stated scales is needed, as well as across-scales research. Scale has been treated philosophically in this essay. But I am reminded of Couclelis's caution, 'Philosophizing in an empirical discipline is a sure sign of trouble' (cited in Abler 1987).

7. Acknowledgements

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References

Abler, R.F. 1987. What shall we say? To whom shall we speak? Ann. Assoc. Am. Geogr. 77: 511–524.

Abler, R.F., Adams, J. and Gould, P. 1971. Spatial organization: the geographer's view of the world. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Basist, A.N. 1989. A comparison of orographic effects on precipitation at 10 regions worldwide. Masters Thesis, University of Georgia.

Beven, K.J., Wood, E.F. and Sivapalan, M. 1988. On hydrological heterogeneity – catchment morphology and catchment response. J. Hydrol. 100: 333–375.

Board, C. 1967. Maps as models. *In* Models in Geography. pp. 671–726. Edited by R.J. Chorley and P. Haggett. Methuen and Co., Ltd., London.

Carlstein, T. and Thrift, N. 1978. Afterword: towards a time-space structured approach to society and environment. *In* Human Activity and Time Geography. pp. 225–263. Edited by T. Carlstein, D. Parkes and N. Thrift. John Wiley and Sons, New York.

Clark, M.J., Gregory, K.J. and Gurnell, A.M. 1987. Introduction: change and continuity in physical geography. *In* Horizons in Physical Geography. pp. 1–5. Edited by M.J. Clark, K.J. Gregory and A.M. Gurnell. Barnes and Noble Books, Totowa, New Jersey.

Clark, W.A.V. and Avery, K.L. 1976. The effects of data aggregation in statistical analysis. Geogr. Anal. 8: 428–438.

Clark, W.C. 1985. Scales of climatic impacts. Clim. Change 7: 5–27.

Cliff, A.D. and Ord, J.K. 1973. Spatial autocorrelation. Pion, London.

Flohn, H. 1981. Climatic variability and coherence in time and space. *In* Food-climate Interactions. pp. 423–441. Edited by W. Bach, J. Pankrath and S.H. Schneider. D. Reidel Publishing Company, Dordrecht, The Netherlands.

Gedgelman, S.D. 1985. Atmospheric circulation systems. *In* Handbook of Applied Meteorology. pp. 3–61. Edited by D.D. Houghton. John Wiley and Sons, New York.

Hart, J.F. 1982. The highest form of the geographer's art. Ann. Assoc. Am. Geogr. 72: 1–29.

Harvey, D. 1969. Explanation in Geography. St. Martin's Press, New York.

Holley, B.P. 1978. The problem of scale in time-space research. *In* Time and Regional Dynamics. pp. 5–18. Edited by T. Carlstein, D. Parkes and N. Thrift. John Wiley and Sons, New York.

Johnston, R.J. 1976. Residential area characteristics: research methods for identifying urban and sub-areas – social area analysis and factorial ecology. *In* Social Areas in Cities, Volume I: Spatial Processes and Form. pp. 193–235. Edited by D.T. Herbert and R.J. Johnston. John Wiley and Sons, London.

Kachanoski, R.G. 1988. Processes in soils – from pedon to landscape. *In* Scales and Global Change: Spatial and Temporal Variability in Biospheric and Geospheric Processes. SCOPE, Vol. 35. pp. 153–177. Edited by T. Rosswall, R.G. Woodmansee and P.G. Risser. John Wiley and Sons, Chichester.

Kirkby, A. 1985. Pseudo-random thoughts on space, scale and ideology in political geography. Polit. Geogr. Q. 4(1): 5–18.

Kotlyakov, V.M., Mather, J.R., Sdasyuk, G.V. and White, G.F. 1988. Global change: geographical approaches (a review). Proc. Nat. Acad. Sci. U.S.A. 85: 5986–5991.

Krummel, J.R., Gardner, R.H., Sugihara, G., O'Neill, R.V. and Coleman, P.R. 1987. Landscape patterns in a disturbed environment. Oikos 48: 321–324.

Mather, J.R. 1974. Climatology: fundamentals and applications. McGraw-Hill, New York.

Meentemeyer, V. 1984. The geography of organic decomposition rates. Ann. Assoc. Am. Geogr. 74: 551–560.

Meentemeyer, V. and Box, E.O. 1987. Scale effects in landscape studies. *In* Landscape Heterogeneity and Disturbance. Ecological Studies, Vol. 64. pp. 15–34. Edited by M.G. Turner. Springer-Verlag, New York.

Miller, D.H. 1970. Geographic scales of field research on the energy-mass budget in the Soviet Union. Prof. Geogr. 22(2): 97–98.

Miller, D.H. 1978. The factor of scale: ecosystem, landscape mosaic and region. *In* Sourcebook on the Environment. pp. 63–88. Edited by K.A. Hammond. University of Chicago Press, Chicago.

Mitchelson, R.L. Concerns About Scale, unpublished.

NASA. 1986. Earth system science overview: a program for global change. Earth System Science Committee, NASA Advisory Council. National Aeronautics and Space Administration, Washington, D.C.

Nir, D. 1987. Regional geography considered from the systems approach. Geoforum 18(2): 187–202.

O'Neill, R.V. 1988. Hierarchy theory and global change. *In* Scales and Global Change: Spatial and Temporal Variability in Biospheric and Geospheric Processes. SCOPE, Vol. 35. pp. 29–46. Edited by T. Rosswall, R.G. Woodmansee and P.G. Risser. John Wiley and Sons, Chichester.

O'Neill, R.V., DeAngelis, D.L., Waide, J.B. and Allen, T.F. 1986. A hierarchical concept of ecosystems. Monographs in Population Biology, Vol. 23. Edited by R.M. May. Princeton University Press, Princeton, New Jersey.

Robinson, W.S. 1950. Ecological correlations and the behavior of individuals. Am. Soc. Rev. 15: 351–357.

Salthe, S.N. 1985. Evolving Hierarchical Systems: Their Structure and representation. Columbia University Press, New York.

Steyn, D.G., Oke, T.R., Hay, J.E. and Knox, J.L. 1981. On scales in meteorology and climatology. Clim. Bull. 39: 1–8.

Stone, K.H. 1968. Scale, Scale, Scale. Econ. Geogr. 44: 94.

Tobler, W.R. 1969. Geographical filters and their inverses. Geogr. Anal. 1: 234–253.

Townsend, J.R.G. 1987. Remote sensing – Global and local views. *In* Horizons in Physical Geography. pp. 63–85. Edited by M.J. Clark, K.J. Gregory and A.M. Gurnell. Barnes and Noble Books, Totowa, New Jersey.

Walsh, J.J. and Dieterle, D.A. 1988. Use of satellite ocean colony observations to refine understanding of global geochemical cycles. *In* Scales and Global Change: Spatial and Temporal Variability in Biospheric and Geosperic Processes. SCOPE, Vol. 35. pp. 287–318. Edited by T. Rosswall, R.G. Woodmansee and P.G. Risser. John Wiley and Sons, Chichester.

Watson, M.K. 1978. The scale problem in human geography. Geogr. Ann. 60B: 36–47.

White, P.S. 1987. Natural disturbance, patch dynamics, and landscape patterns in natural areas. Nat. Areas J. 7(1): 14–22.

Whitelaw, J.S. 1972. Scale and urban migrant behavior. Aust. Geogr. Stud. 10: 101–106.

Young, G.L. 1978. Hierarchy and central place: some questions of more general theory. Geogr. Ann. 60B: 71–78.

Zipf, G.K. 1949. Human behavior and the principle of least effort. Addison-Wesley Press, Cambridge.