GLOBAL CHANGE IN LOCAL PLACES: HOW SCALE MATTERS

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Abstract. Relationships between local and global scales deserve more attention than they have received in the global change research enterprise to date. This paper examines how and why scale matters, drawing on six basic arguments; examines the current state of the top-down global change research paradigm to evaluate the fit across relevant scale domains between global structure and local agency; and reviews current research efforts to better link the local and global scales of attention and action.

1. Introduction

Global changes in climate, environment, economies, populations, governments, institutions, and cultures converge in localities. Changes at a local scale, in turn, contribute to global changes as well as being affected by them. As a result, across a broad range of disciplines and problems, linking the local and the global scales – integrating assessments of population, economy, technology, and environmental change – potentially yields deeper understandings of global change in all its complexity.

To date, the bulk of the research relating local places to global climate change has been top-down, from the global toward the local, concentrating on methods of impact analysis that use as a starting point climate change scenarios derived from global models, even though these have little regional or local specificity. There has been a growing interest, however, in considering a bottom-up approach, asking such questions as how local places contribute to global climate change, how those contributions change over time, what drives such changes, what controls local interests exercise over such forces, and how efforts at mitigation and adaptation can be locally initiated and adopted.

The thesis of this paper is that relationships between these scales, macro and micro, and the interactions between macro-structure and micro-agency affect the way our world works and deserve more attention than they have received in the global change research enterprise to date (e.g., Turner et al., 1990; Root and Schneider, 1995; Schneider and Root, 1996). This is not just an issue in understanding global change. Improving the understanding of linkages between macroscale and microscale phenomena and processes is one of the great overarching intellectual challenges of our age in a wide range of sciences. Biologists struggle to

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understand linkages between molecules, cells, and organisms; ecologists between patches, ecosystems, and biomes; and economists between firms, industries, and economies (Rediscovering Geography Committee, 1997: 95–102; also see, for example, Alexander et al., 1987; Holling, 1992; Levin, 1992; Turner et al., 1993).*

In this paper, we begin by examining how and where scale matters, drawing upon six basic arguments and illustrating each with an empirical example drawn from the literature of climate change and environmental studies. We then examine the current state of the top-down global change paradigm and the practice of integrated assessments of climate change across the relevant scale domains and evaluate the fit between global structure and local agency. Finally, we conclude with a review of some current research and policy efforts to better link the local and the global scales of attention and action.

The paper will draw especially upon the first eighteen months of insights from our own collaborative research effort, the ‘Global Change in Local Places’ study supported by the Mission to Planet Earth program of NASA through the Association of American Geographers. This project is a three-year effort to assess links between local and global change: considering local greenhouse gas emissions, driving forces, and mitigation capacities initially in three study areas, each of about one equatorial degree (latitude and longitude) in size: The Blue Ridge/Piedmont of Western North Carolina, the High Plains/Ogallala Aquifer area of Southwestern Kansas, and the Great Lakes/Manufacturing Belt of Northwestern Ohio.

2. How Scale Matters

In theory, scale matters in studying global change, local dynamics are worth worrying about, and localities can make a difference. For instance, it is clear that some of the driving forces for global change operate at a global scale, such as the greenhouse gas composition of the atmosphere and the reach of global financial systems. But it seems just as clear that many of the individual phenomena that underlie microenvironmental processes, economic activities, resource use, and population dynamics arise at a local scale.

In this paradox lies a dialectic that suggests the fundamental importance of scale. We offer six basic arguments: three about the nature of reality (how the world works) and three about the practice of science (how we perceive and learn about our world). These arguments often seem compelling, almost self-evident. If we go beyond the assertion that scale matters, however, and ask more specifically how and where does scale matter, then the evidence is fragmentary, often anecdotal, and usually specific to individual academic disciplines rather than related to global change more synoptically. But beginning with the reality arguments, there are at

* Similar issues are raised in considering temporal and hierarchical scale as well as geographical scale.

least three reasons to expect that, in ways that are significant for understanding global change, things simply work differently at different scales.

2.1. THE DOMAIN ARGUMENT

The forces that drive global change arise from different domains of nature and society. Turner and his colleagues (Turner II et al., 1990) have broadly divided these domains into the systemic and the cumulative, identifying pathways by which regional problems become global ones. Global systemic changes are direct changes in the functioning of a global system, as exemplified by effects of greenhouse gas emissions on the global climate system or ozone-depleting gases on the stratosphere. Cumulative global changes are those in which the accumulation of localized change is ubiquitous or represents a significant fraction of the total global phenomenon or resource. In this way, widespread localized problems such as groundwater depletion, pollution, or species extinction may become global.

In more detail, Clark (1985, 1987) has sought to examine the domains of climate, ecology, and society in terms of their geographic and temporal scale of operation (Figure 1). Within each domain, the illustrated phenomena are not simple aggregates of smaller and faster types; they are distinctive systems. These systems vary in their spatial scale, with population ecology and farm activities operating locally while many industrial, demographic and meteorological patterns appear at a very extensive geographic scale. At the same time, many meteorological and ecological domains are at temporal extremes, with societal and climatic domains overlapping at an intermediate scale. Clark cautiously suggests that studies of the interaction of these domains, such as in climate impact studies, should begin with domains of the same temporal and geographic scale.

More recently, Root and Schneider (1996) have suggested ‘strategic cyclical scaling’ as an approach to analyzing interactions among processes operating at different climate and ecological scales. This would involve a continuing cycling of studies between large-scale associations that are used to suggest small-scale investigations and smaller-scale associations in order to test the causes and driving forces of the large-scale patterns.

2.2. THE AGENCY ARGUMENT

The domain argument becomes even more salient when it is placed in the context of structure and agency. By agency, we mean intentional human action, and by structure we mean the set of institutions and other regularized, often formal social relationships within which such action takes place. The scale of agency – of direct human action – is often intrinsically localized while the scale of structure is almost always more encompassing. Agency tends to be composed of people whose concerns and sources of influence have a large local component and are shaped by local interactions and by scale-dependent structures such as the boundaries of political jurisdictions.

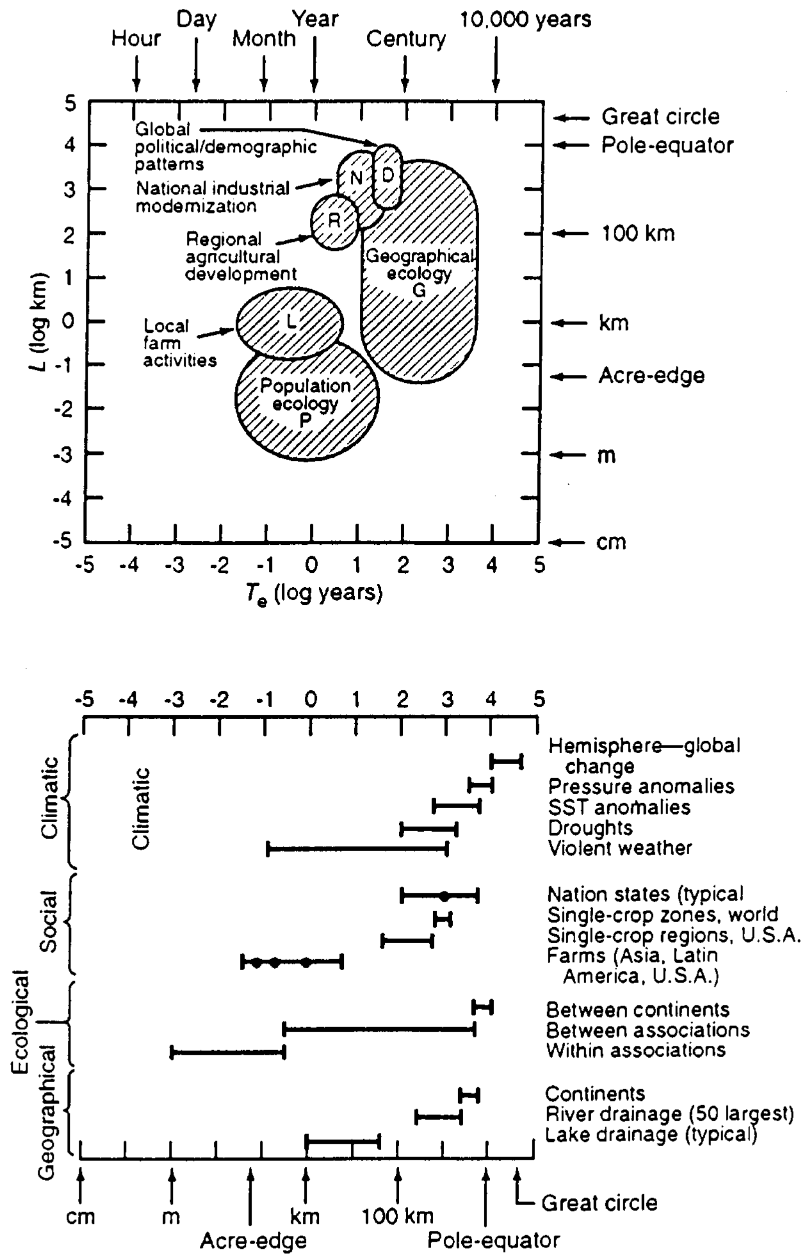

Figure 1. Geographic and temporal scale domains (Clark, 1985).

In theory, this agency argument is especially important where global change mitigation actions are concerned, analogous to, say, hazards behavior, where a large proportion of the major decisions are local (Cutter, 1993). The hazards literature recognizes the role of larger structures that *mandate* some actions by law, regulation or court order, *encourage* actions through persuasion or providing incentives, and *inform* those creating or suffering risk to voluntarily reduce or tolerate the hazard; but the actions themselves are mostly local (Kasperson et al., 1985: 43–66; see also Palm, 1990; Hewitt, 1997). Other literatures reinforce this impression, considering evidence about the scale of human-ecological self-determination (e.g., Wilbanks, 1994: 547–548) and scale and consensual decisionmaking about technology use (e.g., Wilbanks, 1984; Aronson et al., 1984: Ch. 7). For discussions of the role of institutional structures in global change, see Becker and Ostrom (1995), Sampath and Young (1990), and O'Riordan et al. (1998).

Local agency is complicated, however, by the fact that the locale of emissions is not necessarily identical with the locale of control over emissions. Clearly, some local emissions can be traced to local driving forces and decisions, such as electric power generation within an area to meet its own needs. But just as clearly, some local driving forces result in emissions in other areas, such as local consumption of electricity generated in other areas. And many local emissions are the result of forces and decisions made in other areas, such as emissions from through traffic on interstate highways or emissions from local branches of corporations headquartered elsewhere. Seen locally, these external driving forces and decisions may constitute structure.

2.3. THE INTERACTION ARGUMENT

When global structure and local agency interact across very different domains, the associated driving forces, changes, and consequences are still more difficult to predict or understand. Weaknesses in appreciating the interaction of processes moving at different time scales and areal extents, in fact, underly a great deal of the current scientific interest in complexity, nonlinear dynamics, and the search for order amid seeming chaos.

For managed ecosystems, modelers such as Holling (1995: 27) have found that 'a small number of plant, animal, and abiotic processes structure biomes over scales from days and centimeters to millennia and thousands of kilometers' to 'produce a landscape that has lumpy geometry and lumpy temporal frequencies or periodicities'. For Holling, the relevant scale of sizes and speeds and their interactions is well understood in at least a few cases: boreal forests, boreal prairies, and pelagic ecosystems.

For regions where large human activity predominates, however, the interactions are more complex. As one example, in a recent study of nine such 'regions at risk', large subnational zones undergoing great environmental stress (Kasperson et al., 1995), the internal and external interactions appear to be highly diverse and

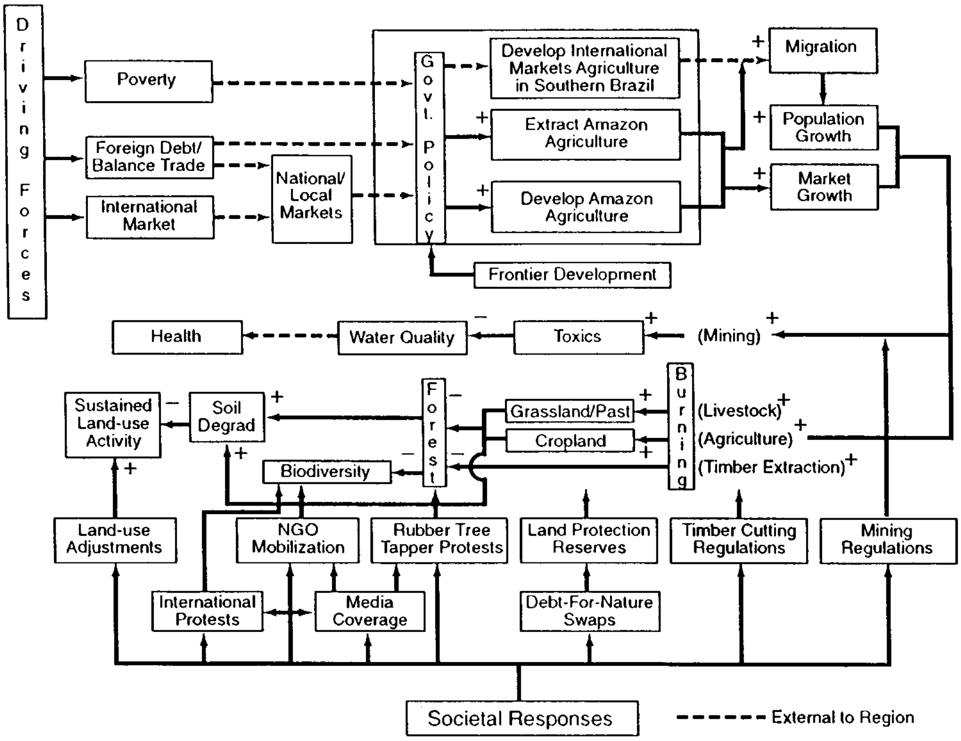

Figure 2. Land use system interactions in Amazonia (Kasperson et al., 1995).

complex, as shown in a typical interaction diagram (Figure 2). Geographic scale is significant in this regard in that the larger the region under study, the larger the proportion of the interactions that are internalized, other things equal.

The three arguments above suggest that scale is an important variable in understanding the reality of global change. But even if things do not in fact work differently at different scales, it can still be argued that global understanding depends in fundamental ways on observations at a local scale for reasons related to the practice of science. Again, we offer three arguments.

2.4. THE TRACTABILITY ARGUMENT

It is argued more and more widely that the central relationships underlying global change are too intractable, too complex to trace at any scale beyond the local, too difficult to keep grounded in direct observations, too likely to become disembodied from actual experience (e.g., Cox, 1997). Essentially, the argument is that the complex relations among environmental, economic, and social processes that drive change at the global scale can only be unraveled by careful locality-specific research.

The central problem in such case-specific research is that, while it is much more tractable, it is much less generalizable. Yet there are many examples of successful comparative studies using case studies as so-called ‘natural experiments’, in which the case studies are carefully chosen for comparability and where possible use a common protocol in order to facilitate theory-building. Besides the abovementioned studies of critical environmental zones, comparative case studies of natural hazards (White, 1974), population density and agriculture in Africa (Turner et al., 1993), and poverty and environment (Kates and Haarmann, 1992) can be readily cited from our own experience (see also Blaikie and Brookfield, 1987).

To illustrate, in the last example only 30 case studies were found in an extensive search of the literature designed to find studies that actually documented at a specific place the widely-held view that poverty and environmental degradation are strongly linked. Despite the fact that the case studies were drawn from Africa, Asia, and Latin America and were not specifically designed to document poverty-environment linkages, a careful content analysis of the studies found a set of common interactive processes. Thus, the available case studies told common tales of poor people’s displacement from their lands, the division of their resources, and the degradation of their environments culminating in three major spirals of household impoverishment and environmental degradation driven by combinations of development/commercialization, population growth, poverty, and natural hazards. In this way, by careful comparison generic principles can emerge even from diverse case studies.

2.5. THE VARIANCE ARGUMENT

It also seems self-evident that the variance detected in a portfolio of observations of geographic areas is likely to be greater when the areas themselves are smaller, at least if the overall geographic expanse covered by the sample is the same. For instance, the variance in greenhouse gas emissions per capita from a random sample of fifty U.S. counties would be expected to be greater than from the fifty states (see, for example, the unnumbered figure in Environment Canada, 1997: 9). In principle, this greater variety in processes and relationships at a more local scale represents an opportunity for learning more about the complex causes and consequences of global change, including the identification of interesting alternatives for mitigation and urgent needs for action that might otherwise be missed. An illustrative example is an investigation of causes of land-use decision making in 192 villages in Thailand, which found a larger variation in behavior than economic theory could explain (Townsend, 1995).

Indeed, the variance in smaller-scale climates can serve as surrogates for more widespread future change. Persistent decadal fluctuations of greater than average temperature (up to 1 °C annually or 2° seasonally) and precipitation (approximately 10% annually) have occurred in most areas of the U.S. during the period of modern records. These ‘natural variations’ that mimic what might occur with global warming have been identified for all climate divisions of the U.S. (Karl and Riebsame, 1984). In one study, such fluctuations were used to study the impacts of potential global warming on the runoff portion of the hydrologic cycle. Highest and lowest runs (5–20 years) of annual temperature and precipitation identified in climate divisions were matched to runs of streamflow in a set of 82 rivers with histories of minimal human interference (Karl and Riebsame, 1989). This example of a 'natural experiment' provided surprising results, with much less than expected impacts of warming on streamflow along with the expected impacts from increased precipitation.

2.6. THE PERSPECTIVE ARGUMENT

Differences in perspective between 'macro' and 'micro' provide many examples of situations where researchers looking at an issue top-down come to different conclusions from those looking at that same issue bottom-up. In the world of energy research, a classic case is analyses of the cost of energy efficiency improvement and other approaches to limiting carbon dioxide emissions, where macroscale economic work has often estimated a significant net cost to the national economy in the U.S., while microscale work in many regions of the world has consistently estimated a net benefit (e.g., Manne and Richels, 1990, vs. Chandler et al., 1991). Similarly, in the same issue of a journal, macroscale analysis of climate change impacts on agriculture finds little net loss in productivity, one region's gains accounting for another's losses, especially with CO_2 fertilization and modest levels of adaptation (Fischer et al., 1994), while microlevel studies identify as especially vulnerable developing country smallholder agriculturists, pastoralists, wage laborers, urban poor, refugees, and other destitute groups (Bohle et al., 1994). Both recognize differences between impacts in larger and smaller countries.

Where global change is concerned, it can be argued that a focus on a single geographic scale tends to emphasize processes operating at that scale, information collected at that scale, and parties influential at that scale – raising the possibility of misunderstanding cause and effect by missing the relevance of processes that operate at a different scale. Focusing exclusively at a local scale can lead to explanations in terms of local causes when some important determinants lie in processes at larger regional and global scales. Focusing exclusively on a larger scale can lead to ready generalizations that are just that – much too general.

For example, at a global scale, there is widespread agreement that environmental impacts and resource use are a function of population, its affluence or wealth, and the nature of its technology and this is expressed as the I=PAT equation. But as one changes perspective, moves down the scale even to large regions, the complexity and richness of explanation increases. In Table I, for instance, drawn from the study of nine environmental zones under great environmental stress (Kasperson et al., 1995), the range of explanatory variables expands beyond population, affluence and technology, to include the economic, social, and political

TABLE I

Human driving forces of environmental change (Kasperson et al., 1995)

Cluster of human driving forces				
Population[a]	Technological capacity[b]	Affluence poverty[c]	Political economy/structure[d]	Beliefs/attitudes[e]
Population growth	Irrigation development	Urbanization	International market	Frontier development
Migration	Mechanization	Poverty	National market	Ethnic/religious views
Natural growth	Fertilization		State policy	Mass-consuming view of nature
	Pasture improvement		Shift to commodity production	Acceptance of corruption
	Industrialization infrastructure		Foreign debt, balance of trade	
	Agricultural intensification		Resource allocation rules and institutions	
			Capital extraction	
			Political corruption	

[a] Population: Increase or decrease in number of people per unit area.
[b] Technological capacity: Movement to a different technology, including shifts in suites of technology.
[c] Affluence/poverty: Level of wealth of an area, generally measured by per capita consumption and well-being.
[d] Political economy/structure: Economic, political, and social institutions that govern resource and environmental use.
[e] Beliefs/attitudes: Ideas and norms of behavior that underlie formal institutions.

institutions that govern resource and environmental use, along with belief systems and attitudes, and poverty emerges as the obverse of affluence and a major driving force in its own right.

3. Scale in Integrated Global Climate Change Assessment

If geographic scale generally matters for some or all of the above reasons, does scale matter in the specific case of the current paradigm of global change research? This dominant paradigm begins with a global atmospheric climate model, which is being rapidly elaborated to include more hydrological, oceanographic, and vegetation features (Sellers et al., 1997). The expanded model, in turn, gives rough estimates of global warming and watering and some crude estimates of their spatial distribution, usually for a benchmark that assumes a doubling of the carbon dioxide in the atmosphere. These intermediate results are then used to simulate possible impacts on nature and human activity. In the latest international assessment, impacts were examined for nine natural terrestrial and aquatic ecosystems and ten managed systems that provide water, food and fiber, and human infrastructure and health (Houghton et al., 1996). The vulnerability of each of these systems was then assessed as a joint effect of the climate impacts and potential adaptations to them. The assessment also examined potentials for mitigation beginning with inventories of available technologies and socioeconomic instruments.

In integrated assessments, all these are put together, including various feedbacks, to get a sense of alternative courses of human action and their associated costs and benefits. There are at least 15 major integrated assessments underway worldwide and, while they differ markedly, systematic comparisons of their inputs and outputs have begun (Toth, 1995). A common characteristic of these models is their low resolution; two-thirds of them, in fact, have a geographic specificity of either the entire globe or of continents (Morgan and Dowlatabadi, pers. comm.), communication), although the integrated assessment enterprise is becoming much more diverse. For example, several recent conceptualizations are not based on global scale models (e.g., Rothman and Robinson, 1997; Parson, 1996).

In Figure 3, we present our own understanding of the scale domains of major activity for each of five links in the causal structure of climate changes and consequences: *emissions and land cover change* (fossil fuels, landfills, agriculture, deforestation); that alter *radiative forcing* (trace gases, aerosols, and reflectivity); leading to *climate change* (temperature, precipitation, extreme weather), with major *impacts* (ecosystems, agriculture, coasts, health), and *responses* (mitigation, adaptation). We employ four levels of geographic scale: global, regional (continental, subcontinental, economic/political unions), large area (states, provinces, large basins and 5–10° grids), and local (1° grid squares, small basins, cities). We then contrast these with our appraisal of the current state of assessment – how the scale of observation, research, and policy relates to the scale of the major activities

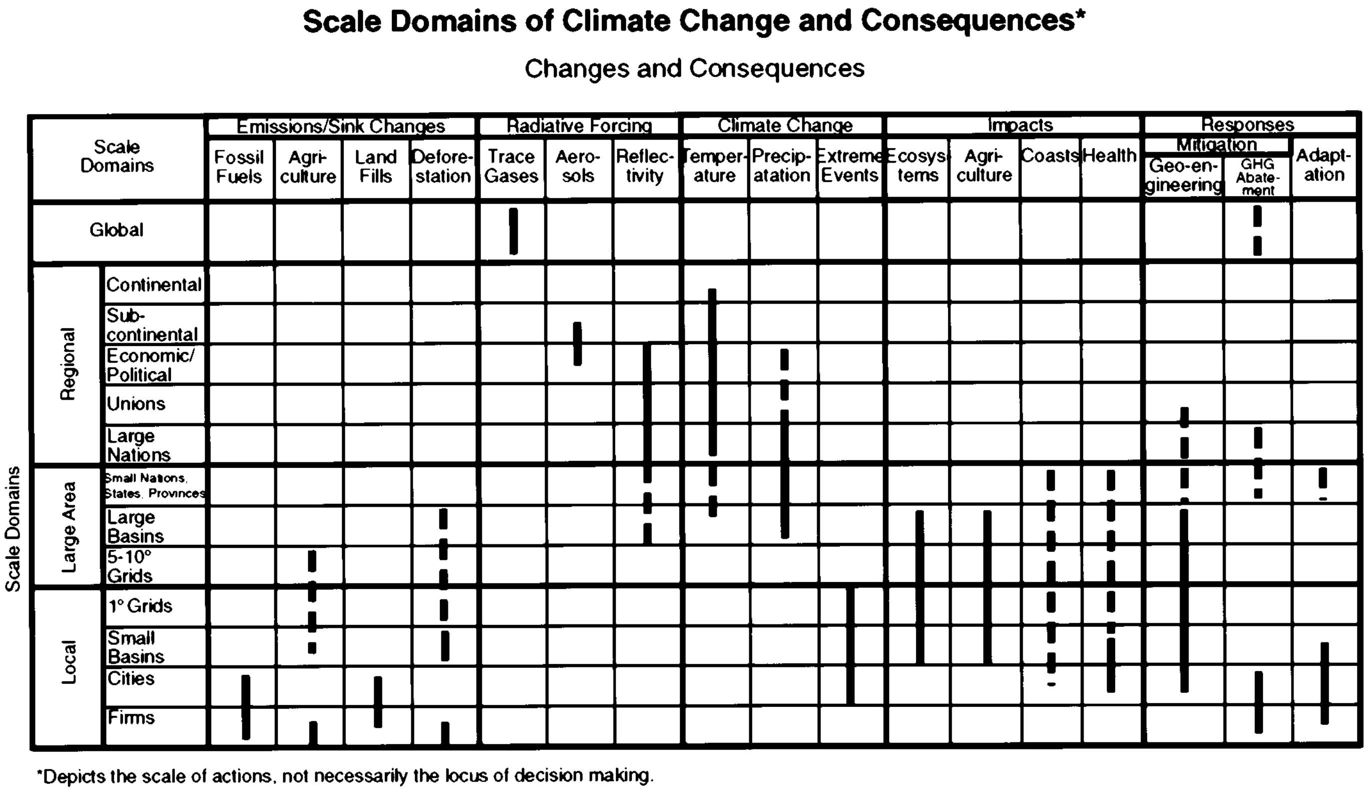

Figure 3. Scale domains of climate change and consequences.

in each of the causal links. Overall, while the domains of major activities vary within each of the five links of cause, forcing, change, consequence, and response, there seems to be an envelope of domains that in many respects moves upward from locally initiated emissions to atmospheric driving forces, then downward to the local scale of efforts to abate, mitigate, and adapt – although non-local driving forces for local actions, and in some cases national or even global actions, underlie much local human agency.

3.1. EMISSIONS AND LAND COVER CHANGE

The human activities that can lead to climate change are very local. The major activities are those related to fossil fuel production and burning (manufacturing, electricity generation, transportation, and household heating), to forestry and agriculture (livestock, wetlands, fertilizers, land clearing, timber production), to waste disposal (landfills and incineration), and to ozone depleting chemical (ODC) manufacture and use. They emit trace gases of CO_2, CH_4, N_20, and ODCs that accrue in the atmosphere, increase positive radiative forcing, warming the surface of the earth. They emit airborne particles, mainly sulfate aerosols, that decrease positive forcing, and thus act regionally to counter greenhouse warming potential. They also change the land cover of the earth, leading to changes in reflectivity (albedo) that can also affect radiative forcing and serve to release or store carbon to or from the atmosphere. Taken together, these factories, vehicles, households, fields, and animals number in the billions of point or small area sources of emissions, aerosols, and land cover change.

But estimates of emissions of greenhouse gases and aerosols are to date global and regional and are primarily limited to CO_2. Estimates of CO_2 emissions from fossil fuel consumption and cement production are currently available for all nations. In some countries, there are estimates for large areas, for example about half the states of the United States. And for all countries, there are now two sets of $1^\circ \times 1^\circ$ CO_2 emissions data for the entire world, but these are the same as the country data, allocated to each grid by the estimated proportion of the population within that grid square. The population is also a rough estimate and differs between the two sets (Marland, pers. comm.). Aerosol estimates, particularly of sulfates, are available for most industrialized countries (Graedel et al., 1995). Detailed land cover data are available as well, some at the scale of a square kilometer (AVHRR), and new sensors will soon be in place that will offer much more detail. Using satellite observations, it is possible to estimate change in land cover for most places over the past decade (e.g, Dobson et al., 1995).

Looking to the future, a set of widely accepted common reference scenarios project future emissions for the globe and major regional divisions based essentially on population, economic growth, and some assumptions as to technological change – the IPAT variables. Regional air pollution models for North America, Europe, and most recently Asia provide similar data for future aerosol distributions. There are no equivalent projections of land cover change but this is a major research focus, albeit in its early stages (e.g., Turner et al., 1995).

This gross misfit between the billions of point and small area sources of emissions and the aggregated data sets by nation, region, and world is not of concern either for the purposes of calculating radiative forcing, because of the global accrual and diffusion of gases, or for international responses, agreements essentially made among nations. The fit is not so good, however, as one seeks to implement such agreements or to encourage abatement, mitigation, or adaptation through actions by emitters or directly impacted parties. Inventories of emissions serve as the basis for identifying efforts at mitigation; knowing the bundle of greenhouse gases generated locally enables the emitters to address their specific sources. Unfortunately, except for some cities, there are few data sets of local emissions; and even when desired, they are usually difficult to compile.

In our local place research, we have adapted the EPA version of the international guidelines (IPCC) to calculate emissions inventories for our 1° sites. We have found that current EPA protocols for state emissions are clearly too complicated and data-intensive for most local studies. Even in the data-rich United States, many needed data sets are not available at local or county levels. Examples abound: fossil fuel consumption – the major single variable in emissions – is not measured locally; electricity generation and consumption data rarely fit the scale of study areas; and ODC estimates rely on national-scale production data. Even when emissions data can be allocated locally, they do not address the people and the organizations that produce and can potentially control and mitigate emissions. For example, householders cannot tell for which emissions they are responsible. Residential fossil fuel consumption figures include only in-house use. Emissions from electricity consumption for households are estimated from aggregate utility supply data; energy consumption for movement is estimated from aggregate transportation sector data; some methane originating in households is measured as waste in municipal land fills; and household ODCs are based on per capita allocation of national production, much of which is actually consumed industrially.

3.2. RADIATIVE FORCING

As for radiative forcing, trace gases of CO_2, CH_4, NO_x, and ODCs accrue from local emissions, are estimated at national and regional scale, but rapidly diffuse and are operative for all intents and purposes at global scale. Global carbon concentrations in the atmosphere have been observed since 1958, other trace gasses (methane, NO_2, and ODCs) since 1978. Sulfate aerosols accrue somewhat less widely, mostly concentrated in industrial regions, and thus act regionally to counter greenhouse warming potential. Changes in land use that change the reflectivity (albedo) of the earth's surface accrue locally and store or release carbon, requiring extensive change over large areas to significantly affect global climate. While there is much to be learned about the distribution of some gasses and aerosols in the atmosphere, there is a good fit between the scale of what is observed and what needs to be known for both scientific understanding and policy of the atmosphere.

3.2.1. *Climate Change*

Three major features of climate change are of particular interest: temperature, precipitation and extreme weather events. The scale at which these major parameters of climate might change varies by several orders of magnitude. Extreme weather occurs at a scale of 0.1 to 1,000 km^2; precipitation or the lack of it in major droughts occurs at geographic scales of 1,000 to 10,000 km^2, and temperature change as evidenced in historic warming trends is manifest in areas larger than 10,000 km^2 (Clark, 1985). The scale at which the major parameters of climate are observed, measured, modeled, or perceived in global climate modeling generally fits poorly with these scales.

The issues are partly a function of model resolution, the homogeneity of observations, and the perception of significant differences. In terms of *models*, until recently available resolutions provided outputs for 5 and 10 degree grids, thought to be reliable primarily for temperature and only as large latitudinal bands or continental zones. In terms of *observations*, an area the size of the contiguous U.S. is divided into 344 climatic divisions as distinct areas of somewhat homogeneous sets of observing sites. *Perceptions* of significant differences range from the dozen or so distinctive climate types found on world atlas maps to popular perceptions that divide the U.S. into snowbelts and sunbelts. Local agency (and related policymaking) may depend on information at a quite local scale.

Driven by these needs, climate change forecasting is being downscaled as rapidly as the state of the art can manage. For instance, the multiparty Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) in the United States is now producing forecasts at 1 degree scale, and efforts are being made to develop forecasts at a one-half degree scale, equivalent to a square approximately 50 kilometers on a side (Pan, 1998). Even so, there remains a significant gap between the climate change forecasting models, the scale at which weather and long-term climate expresses itself, and the local weather of everyday experience.

3.2.2. *Impacts*

Current interest in the impacts of human-induced climate change focuses on 9 distinctive natural terrestrial and aquatic ecosystems and the 10 managed systems that provide water, food, and fiber, human infrastructure and health (IPCC, 1995). Some of these systems are actually climate-bounded, i.e., climate helps define their areal extent. For such climate-bounded activity, climate change impacts may show up first as shifts in the margins of ecosystem, crop region, shoreline, or disease vector habitat. The scale of such impact areas varies considerably but tends to approximate large areas or their borders.

A good approximation of the scale of climate bounded ecosystems is the 52 ecoregions of the United States that range in size from the 9,500 km^2 of the Black

Hills of south Dakota to the 750,000 km^2 of the Great Plains/Palouse Dry Steppe region, a spatial range on the order of the states themselves (Bailey, 1995). Crop regions are somewhat similar, with the major crop regions approximating larger ecoregions that encompass 3-8 states in areal extent (USDA, World Agricultural Outlook Board, 1987). A distinctive region is the thin but continuous sliver of coastal land subject to sea level rise that – e.g., for a 1 meter rise in sea level – can range from several kilometers on small islands, thousands of kilometers for medium sized countries, to tens of thousands of kilometers for low-lying areas in Bangladesh, China or the U.S. Disease vector habitat changes can range from large belts of malaria infestation to river-constrained onchosoriasis, and impacts of changed or intensified tracks of extreme weather events (hurricanes, tornadoes, hail, wind) can likewise range from limited bands of vulnerability to large regions.

Climate change impact analysis that seeks to assess the positive and negative impacts of future climate change on natural ecosystems and human activities has been, to date, matched in only a very preliminary way with the relevant scales of large areas or their local borders. Since most assessment begins with some modeled climate change, the poor resolution of climate change modeling has focused impact assessment on major ecosystem types and generic economic sectors, in the main at the scale of subcontinents or large drainage basins (e.g., Watson et al., 1998). Studies of agricultural impacts have been based on major crop types and ecosystems on large biomes. An exception has been the areas that would be impacted by sea level rise, which can be very locally specific. Overall, what is striking about impact assessment is its generic quality and lack of place-specific content, when 'average impacts' over large areas have limited value for discussions of place-oriented response. Once again, however, recent developments are encouraging (see Section 6 of this paper).

3.2.3. *Responses*

Responses to concerns about global climate change concerns can involve abatement, mitigation, or adaptation. Mitigation can take the form of 'geoengineering' that either seeks to accelerate the removal of greenhouse gases from the atmosphere or to change the earth's radiation balance. The most feasible of these very large interventions (and most are not) is to increase carbon storage in forests, soil, and perhaps the oceans, all of which require responses that may be local but cumulate to large areas. The other major form of impact prevention is emissions abatement. There are numerous ways to reduce GHG emissions, mostly focused on actions that are very local (recall the billions of point sources). But these individual actions are structured by international agreement, national policy, and corporate decision. Adaptation is a response to inevitable climate change and seeks to reduce the natural and social vulnerability to such change. Even more than abatement, adaptation takes place locally; but, like abatement, it can similarly be assisted by global, national, and corporate policies. Taken together, this range of responses reflects a combination of more or less locally-based decisions and broader scale driving or enabling forces (which, in turn, are often shaped by localized or regionalized political considerations).

There has been relatively little place-specific study of appropriate responses to global warming, either in abatement or adaptation. Because energy use is such a large source of emissions, efforts to abate emissions draw upon the rich historical experience with reducing energy consumption and shifting energy sources in the past quarter-century. But most of this analysis is generic rather than place-specific, organized by technological or economic sector categories and seldom directly relevant to crafting a realistically feasible current response to concerns about global warming. Abatement by carbon storage in ecosystems, however, is usually discussed in more geographic terms of large-area ecosystems and land uses.

Adaptation as a whole is understudied in the prevailing paradigm. Where it is addressed, it is usually by analog, arguing that current adaptations to extremes of natural hazards: (drought, flood, storm surge, sea-level rise, pests, and infectious disease) provide a pattern of adaptive response for future climate change. In what is currently the most important integrated assessment to date, the IPCC 2nd Assessment, adaptation figures prominently in the title of the second volume (Watson et al., 1996) but, alas, not in the content. Of the 728 pages of substantive text, about two thirds are devoted to impacts, one-third to mitigation and only 32 pages to adaptation.

There is thus a grave mismatch between the knowledge that is needed to act locally and what is currently being done globally to generate knowledge about climate change, its impacts, and responses to concerns. Consider an illustration from our own research (Exhibit 1), which shows that even well-motivated local interests need to know their own sources and bundles of greenhouse gases generated from their local place, since these differ considerably from national or even state averages.

But even our preliminary work has identified two further barriers towards encouraging local responses even when a local emissions inventory is available. The first of several focus group meetings in our North Carolina site has demonstrated that individuals have great difficulty linking their individual activities and decisions to changes at the global scale. Partly this is conceptual: what portion of the relevant bundle of greenhouse gases produced by a locality is subject to control or influence by local people? Much of the local bundle of greenhouse gases is emitted in the course of activities that serve non-local people (natural gas production and transmission, automobile and furniture production) but at the same time that provide local employment and income. Much of local consumption is associated with emissions elsewhere (e.g., local consumption of electricity generated externally). And a small but perhaps significant portion of the bundle may come from non-local sources (emissions from vehicles simply passing through the area). Even more difficult to assess is the locus of control over (or influence on) each set of emission-generating or emission-encouraging activity: where are decisions to

EXHIBIT 1. Differences in local scale compared with broader averages: An example

The Blue Ridge-Piedmont site for the Global Change in Local Places project (western North Carolina) contains a mix of forest and manufacturing in a rapidly growing area; the Great Lakes-Manufacturing site (northwestern Ohio) features rustbelt restructuring of heavy industry; and the High Plains-Ogallala site (southwestern Kansas) combines low population with intensive irrigated crop and beef production.

While fossil fuel emissions are important everywhere, specific sources vary among sites, and emission patterns differ significantly from global, national, or even state averages. Power plant emissions and biomass burning are important in the North Carolina area, while natural gas extraction and transmission dominate in the Kansas area. Other greenhouse gases vary widely between sites; for instance, nitrous oxides from fertilizer and methane from cattle and natural gas leaks are important in the Kansas site, and water vapor, an ignored green house gas (GHG) because of its global equilibrium, but with a potential for moderating local effects of global warming, is a 'fossil' source at the Kansas site. Despite extensive timber extraction, forests act as a carbon sink at the North Carolina site. At local levels, the importance of Ozone Depleting Chemicals (ODCs) is indeterminate, at least partly because information is unavailable. At all three sites, per capita emissions are 5 to 20 times greater than national per capita estimates; and within sites, county emissions differ by up to two orders of magnitude.

Temporal differences are also large. Between 1970 and 1990, greenhouse warming potential (GWP) increased by 143% in the North Carolina site, twice the rate for North Carolina as a whole and considerably faster than for United States as a whole, where GWP probably decreasing during that period. Preliminary data from the Ohio site show a striking decrease in industrial GWP sources over time. There is also great volatility in emissions among localities, primarily from fluctuations in industrial sources. But somewhat unexpected were the large spikes in emissions from catastrophic causes that were observed in some cases: e.g., chemical plant fires at the Ohio site.

These differences are not simply curiosities of averaging and aggregating but shed light on what is going on more generally and help to structure appropriate local concerns and responses.

undertake emission-related activities made, and where might decisions be made to reduce emissions? Partly the issue is motivational: people are being asked to take local actions on global changes distant to both their place and time. Barring better information on expected local impacts, this will be a continuing difficulty.

4. Linking Global Structure to Local Agency

This mismatch between global structure and local agency is beginning to be recognized, and important research and policy efforts to link the global and the local are underway. We see three central research questions being pursued in order to downscale the current top-down research paradigm, incorporate the differences in perspective from bottom-up studies, and to improve our understanding of local agency: (1) Can the dominant top-down research paradigm be made more useful for local places? (2) Can the differences in perspective between the global and local scales be reduced or used in understanding and acting upon global change? (3) What can local areas and actors actually do; and what might they want to do about global change?

4.1. DOWNSCALING THE RESEARCH PARADIGM

With the limitations of the top-down paradigm increasingly recognized, the global climate change research community is working hard to improve the geographic and topical richness of global climate models, to move downscale and to cross scales more carefully (both numerically and empirically), to make the linkages in the integrated assessment models more relevant to local and regional concerns, and to improve the forecasts of regional (if not local) impacts and thereby to encourage suitable responses. Current activities include downscaling analyses of emissions and atmospheric driving forces, models of climate change, estimations of impacts, assessments of responses, and efforts at integrated assessment. Such downscaling efforts are both numerical (i.e., model-based) and empirical (i.e., statistically based), with empirical methods growing more rapidly in use.

4.1.1. *Atmospheric Driving Forces*

While the available estimates of greenhouse gas emissions are useful as inputs to top-down models, further activity is underway to calculate (or at least estimate) greenhouse gas emissions at a national scale across the world, along with identifying a range of potential impacts, as a prelude to discussing national and international mitigation policy initiatives (Graedel et al., 1993, 1995). For the OECD countries, this calculation or estimation has already been done, and a range of studies are under way in 55 developing and transitional countries, intended not only to estimate national greenhouse gas emissions and some regional or sectoral impacts but also to build national capacities to undertake such studies (Dixon et al., 1996).

Also at the national level, comparative decompositions of the driving forces of CO_2 production for ten countries over 18 years have made a major contribution to understanding the considerable differences in sources and per capita and per dollar emissions even between highly industrialized countries (Schipper et al., 1996).

In the U.S., the EPA has downscaled the IPCC methodology for calculating emissions, making appropriate modifications suitable for calculating state-wide emissions, and is supporting studies in more than 30 states. At its three study sites in the U.S., the GCLP project has further adjusted the EPA methodology in order to calculate county emissions for 1990 and to backcast these to 1970 and 1980. Using a more simplified emissions methodology for CO_2 and methane, scores of cities that participate in the International Council for Local Environmental Initiatives (ICLEI) urban climate change initiative around the world have estimated their greenhouse gas emissions as a starting point for discussing policy alternatives for reducing them, and analyses have been conducted by ICLEI for individual firms as well (see the section on Local Agency, below).

4.1.2. *Climate Change*

New efforts are being made to downscale current model outputs in order to provide more credible forecasts of subnational climate changes and impacts. A recent paper by Jenkins and Barron (1996), for example, reported results of an attempt to project climate changes for U.S. regions at a finer scale. The authors found that a doubling of the atmospheric CO_2 concentration would mean higher wintertime precipitation for the northeastern U.S., while the southwestern U.S. would be substantially drier in the winter. In the summer, warmer global climate conditions would lead to increased precipitation in the southern U.S. As an example of a more detailed kind of analysis, they projected that the Susquehanna River basin would get more precipitation during every season in a doubled CO_2 world, with almost a third more in spring and summer. This is the kind of detail needed to support policy discussions about regional vulnerabilities and response strategies, if it can be provided with a level of uncertainty that is low enough to attract serious attention from non-scientists.

In a parallel effort, global change research is also focusing on shorter-term climate forecasting, moving from the decades-to-centuries perspective of greenhouse warming to also include seasonal and interannual forecasts, the reliability of which for certain areas has improved considerably. Such forecasts are often much more relevant for local places and provide opportunities for a better understanding of climate sensitivity and improving response to climate forecasts.

4.1.3. *Impacts*

Efforts to compute the place-specific impacts of global climate change have relied on two basic approaches. First, because forecasts at regional scales of resolution may vary considerably from model to model, multi-model outputs are often used to provide a range of potential regional climate changes on which to base estimations of future consequences. An alternative is to use current climate variability and ecosystem and economic sensitivity to simulate regional climate change impacts from prescribed hypothetical changes.

An example of the first approach is the Rosenzweig–Parry–Fisher (1995), Rosenberg and Parry (1994) study of global agriculture. Based on projections from three global climate models, they estimate potential grain yields under several plausible scenarios for climate change, suggesting that a doubling in the global carbon dioxide concentration in the atmosphere will cause decreases in global food production. Parry has also used historic climate variability data to suggest how, at the margins of agricultural regions, shifts in productivity might take place. This general approach has been widely used in forecasting place-specific changes in ecosystems using the Holdridge triangle life zone (Holdridge, 1967; Emanuel et al., 1985; Pitelka, 1997). A further example is attention to impacts of climate change in Mexico by Liverman and her colleagues (Liverman, 1992; Conde, Liverman et al., 1997).

A variant on this historical approach is to choose some time period with notable but relevant extremes of climate as an analog of impacts and responses. Thus the MINK study used as an archetype the actual weather during the great U.S. drought of the 1930s but applied those weather patterns to the current ecosystems, economy, and population of the four states of Missouri, Iowa, Nebraska, and Kansas (Rosenberg, 1993). In Canada, a recently completed regional study of the Mackenzie River basin used a recent period of considerable warming, with impacts that have been observed by the area's current population (along with model-based scenarios), to simulate what long-term impacts to global warming might be in this far northern region (Cohen, 1997a,b).

As thought-provoking as this body of research has proved to be, however, it continues to be derived more often from a top-down perspective, beginning with gross-scale estimates of large-area climate changes rather than arising from detailed local realities that are relevant to understanding global change issues. One reason, of course, is that local impacts are often affected by what happens elsewhere; but this reality can be treated by either a top-down or a bottom-up research design.

4.1.4. *Responses*

Although it is clear that many responses will necessarily be based on localized actions and that, in the United States, national responses will be shaped by the political influence of local and regional constituencies, much of the discussion of responses to concerns about global climate change has in fact been focused on international agreements among nations: e.g., IPCC and Agenda 21. One significant recent move to downscale this kind of assessment is the first U.S. National Assessment of Consequences of Climate Variability and Change, which includes twenty regional assessments of vulnerabilities to impacts and potentials for adaptation and coping. The national assessment report is scheduled for delivery to the U.S. Congress by the beginning of the year 2000.

4.1.5. *Integrated Assessments*

Making the results of integrated assessments of global climate change more useful to decision makers depends fundamentally on making the results more specific to the concerns of localities and regions, the scale at which so many policies are enacted and decisions taken. Efforts are being made, for instance, by Carnegie–Mellon University to downscale the results of integrated assessment models (Dowlatabadi and Morgan, 1993), and the state of the art is also being advanced at Penn State's Center for Integrated Regional Assessment (Knight et al., 1998) and at the Oak Ridge National Laboratory (Turner and O'Hara, 1995). It should also be noted that such efforts at a national scale as the Country Studies program are trying to develop capacities to do integrated assessments for some very small countries, where the level of detail is equivalent to fairly small regions in larger countries.

The challenge, however, is one of communication as well as analysis. An extensive recent study by William Clark and his colleagues at Harvard University has considered what would need to be done to make the results of integrated assessment modeling more useful for decision making at the local level (Clark et al., 1998).

4.2. INCORPORATING DIFFERENCES IN PERSPECTIVE

The variability and volatility of emissions in the three GCLP study areas and the ways local emissions and trajectories differ from the trajectories for larger aggregates argue powerfully for the importance of incorporating local knowledge in global change research. We expect the importance of local knowledge and local contacts to become even more salient as we address driving forces and mitigation in the GCLP project's next stages. Our experience to date shows how respected researchers from the local area, linked through a set of networks with former students and local decision makers, can elicit information from local actors (not necessarily convinced at the outset that they have a stake in global environmental change issues) that would likely be unavailable to unfamiliar experts from distant sites. But this kind of input to global change research is dramatically different in its approach, culture, and participation from the dominant top-down perspective.

Supporting this preliminary conclusion was an exercise at a June 1998 Workshop on Global Environmental Assessment and Public Policy, organized by the Harvard University Committee on the Environment (proceedings not yet published). One of three breakout groups reviewed several dozen efforts to connect national or global expertise with local action, and a strongly-supported empirical finding was that the process is far more effective when general expertise is focused on interactions with experts at the local scale, who then provide the linkage with local decision makers.

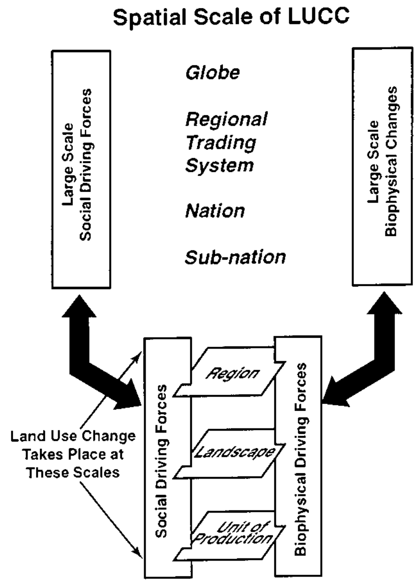

Figure 4. Spatial scale of LUCC (Turner et al., 1995).

One way of overcoming differences between top-down and bottom-up perspectives would be to bridge the gap between detailed local case studies and global or regional models of climate change and its implications. As noted above, in order to keep them tractable, the 'integrated' models of global change started with physical models, transforming them into biophysical models with parameterized linkages with human society, and only recently considering impacts on biomes and economic activity and the economics of abatement and adaptation.

Any real effort to tease out the complex interaction of society, polity, economy, and ecology, however, is still limited to the medium of case studies, the favored approach of local-scale researchers. A central challenge in global change research is determining out how to link the richness of case study insights with the rigor and malleability of the global models. One prototype for such a linkage is the international Geosphere-Biosphere study dealing with land use and land cover change (LUCC), which is trying to develop a conceptual map for case studies, both existing and proposed, and eventually to link their insights to regional models (Turner et al., 1995). Figure 4 shows the kind of thought process that is involved, moving from a global scale down to the more detailed scale where land use changes actually take place. Another approach to regional-scale modeling is being taken by IIASA (e.g., Antoine et al., 1997).

4.3. UNDERSTANDING LOCAL AGENCY

Local agency – or, more precisely, agency at a sub-national scale – is being explored by the global change research community in at least three levels in terms of scale. One is a regional scale, where Cohen's report from Canada is a good example (Cohen, 1997); in the U.S., this has often taken the form of data collection at the state level, with particular support from EPA (EPA, 1995). A second level is the city or metropolitan area or equivalent sub-regional locale (e.g., Harvey, 1993; ICLEI, 1996a). The third level is focused on people and organizations (e.g., ICLEI, 1996b).

Two examples illustrate current activities. First, EPA has provided financial and technical assistance to the states in this country to compile comprehensive greenhouse gas emission inventories, state action plans, and innovative demonstration projects. These activities help both to increase the base of information and to build capacity and momentum at the state level to address global climate change issues; and 29 states and Puerto Rico have participated in at least one of the programs so far. The second example is the pathbreaking contributions of ICLEI, which is trying to foster greenhouse gas emission reductions from cities and counties. With this goal in mind, the council has launched three voluntary initiatives, called the 'urban CO_2 reduction campaign', the 'green fleets campaign', and in 1995 the 'cities for climate protection' campaign.

Finally, what of individuals and small social groupings? Work on this question often begins with studies of individual or group perceptions of climate change issues, surrounded by attitudes, opinions, and beliefs as well as information. Typical are national surveys such as a recent survey of 1,200 U.S. registered voters, who were asked: How serious a threat do you think global climate change is? 34% answered 'very serious', and 37% said 'somewhat serious'. But only 49% thought the U.S. should sign an international protocol to reduce emissions while 41% opposed such action, when posed with contrasting arguments that the U.S. 'as the source of the largest percentage of these emissions, should be a leader in this area and sign this agreement' or 'that the agreement could hurt the U.S. economy by reducing our ability to compete with some nations that would not have the same restrictions' (Bureau of National Affairs, 1996).

More searching analyses explore the understanding and beliefs that underlie such opinions and indicate considerable confusion among lay people as to the causes and consequence of global climate change, particularly confusing greenhouse gas warming with atmospheric pollution and ozone depletion (Kempton, 1991; Kempton et al., 1995).

4.4. FURTHER STEPS

From this review, based on our ongoing GCLP project and the extensive literatures, we suggest that the global change research effort would benefit from a greater emphasis on a more local scale of data gathering and analysis and on bottom-up perspectives on global change issues, as well as more attention to interactions among domains and processes operating at different scales. This does not mean, of course, that scale is necessarily the preeminent variable in understanding global change, but it seems clear that scale is a key piece in the puzzle.

Toward this end, we would suggest that three significant kinds of research are needed to fill the current scale-related gaps, the first two of which are addressed in part by the LUCC science plan:

(1) Developing a bottom-up paradigm to meet the top-down paradigm midway, putting localized observations into a conceptual structure that has a degree of coherence comparable to the current body of global change research. As the LUCC science plan unfolds, land use and cover change projects in all major continents are moving in this direction, beginning to link scales ranging from households to large regions.

(2) Developing a protocol for local area studies of global climate change issues that will increase the comparability of case studies carried out by a wide variety of parties with a wide range of financial and technical resources. Current experience with the comparative case study aspect of LUCC indicates that this is a major challenge: that developing and implementing truly common protocols is very difficult to achieve. Based on our GCLP experience, such a protocol will need to be ‘layered’, in the sense that many local area studies will lack the time, funding, and expertise to use a detailed statistical protocol. At the heart will need to be a description of a *process* for conducting a local area study related to global change: guiding a local study design through the steps to be taken, the questions to be considered, and the judgment decisions to be expected, along with guidelines for making them. The process should include guidelines for involving local stakeholders as appropriate.

(3) Building a system for long-term observation, monitoring, and analysis of the interaction of global forces at a local scale and the implications for sustainable environmental management across the whole spectrum of scales. One approach would be to extend the concept of Long Term Ecological Research Stations (LTERS), currently limited to natural ecosystems that are mostly unperturbed by human activity, to Long-Term Human Environmental Research Stations (LTHERS) that would focus on observing and analyzing human ecological change. Regional universities could provide the trusteeship for local LTHERS observatories that government agencies provide for the LTERS. The prospect is that such observatories could produce a reliable longitudinal data base (i.e., containing consistent periodic measurements over a long span of time) on human impacts and responses to global climate change and other long-term environmental changes.

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References

Alexander, J. C. et al. (eds.): 1987, *The Micro-Macro Link*, University of California, Berkeley, CA.

Antoine, J., Ficher, G., and Makowski, M.: 1997, 'Multiple Criteria Land Use Analysis', *Appl. Math. Comp.* **83**, 195–215.

Aronson, E. et al.: 1984, *Energy Use: The Human Dimension*, W. H. Freeman, San Francisco.

Bailey, R. G.: 1995, *Description of the Ecoregions of the United States*, U.S.D.A. Forest Service Misc. Pub. 1391, U.S. D. A. Forest Service, Washington.

Becker, C. D. and Ostrom, E.: 1995, 'Human Ecology and Resource Sustainability: The Importance of Institutional Diversity', *Ann. Rev. Ecol. System.* **26**, 113–135.

Blaikie, P. and Brookfield, H.: 1987, *Land Degradation and Society*, Methuen, London.

Bohle, H. G., Downing, T. E., and Watts, M. J.: 1994, 'Climate Change and Social Vulnerability', *Global Environ. Change – Human Policy Dimensions* **4**, 37–48.

Bureau of National Affairs: 1996, *Environment Poll Demonstrates Public Concern about Climate Change, Support for Treaty*, Press Release, December 1996, Washington D.C.

Chandler, W. U. et al.: 1991, 'Climate Change and Energy Policy in Eastern Europe', *Energy* **16**, 1423–1435.

Clark, W. C.: 1985, 'Scales of Climate Impacts', *Clim. Change* **7**, 5–27.

Clark, W. C.: 1987, 'Scale Relationships in the Interaction of Climate, Ecosystems, and Societies', in Land, K. C. and Schneider, S. H. (eds.), *Forecasting in the Social and Natural Sciences*, D. Reidel, Dordrecht, pp. 337–378.

Clark, W. C., Jaeger, J., and van Eijndhoven, J. (eds.): 1998, *Learning to Manage Global Environmental Risks*, MIT Press, Cambridge, MA.

Cohen, S. J.: 1997a, 'Scientist-Stakeholder Collaboration in Integrated Assessment of Climate Change: Lessons from a Case Study of Northwest Canada', *Environ. Model. Assess.* **2**, 281–293.

Cohen, S. J.: 1997b, 'What If and So What in Northwest Canada: Could Climate Change Make a Difference to the Future of the Mackenzie Basin?' *Arctic* **50** (4), 293–307.

Conde, C. and Liverman, K. et al.: 1997, 'Vulnerability of Rainfed Maize Crops in Mexico to Climate Change', *Clim. Res.* **9**, 17–23.

Cox, K. R.: 1997, *Spaces of Globalization*, Guilford, New York.

Cutter, S.: 1993, *Living with Risk*, Edward Arnold, London.

Dixon, R. K. et al.: 1996, 'Greenhouse Gas Mitigation Strategies: Preliminary Results from the U.S. Country Studies Program', *Ambio* (February), 26–32.

Dobson, J. E. et al.: 1995, *NOAA Coastal Change Analysis Program: Guidance for Regional Implementation*, NOAA Technical Report NMFS 123.

Dowlatabadi, H. and Morgan, M. G.: 1993, 'Integrated Assessment of Climate Change', *Science* **259**, 1813, 1932.

Emanuel, W. P., Shugart, H. H., and Stevenson, M. P.: 1985, 'Climate Change and the Broad-Scale Distribution of Terrestrial Ecosystem Complexes', *Clim. Change* **7**, 29–43.

Environment Canada: 1997, *The Canada Country Study: Climate Impacts and Adaptation, National Summary for Policy Makers*.

EPA: 1995, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions* (2nd ed.), U.S. Environmental Protection Agency, Office of Policy Planning & Evaluation, EPA 230-B-95-001.

Fischer, G., Frohberg, K., Parry, M. L., and Rosenzweig, C.: 1994, 'Climate Change and World Food Supply, Demand and Trade: Who Benefits, Who Loses?' *Global Environ. Change* **4**, 7–23.

Graedel, T. E. et al.: 1993, 'A Compilation of Inventories of Emissions to the Atmosphere', *Global Biogeochem. Cycles* **7**, 1–26.

Graedel, T. E. et al.: 1995, 'Global Emissions Inventories of Acid-Related Compounds', *Water, Air Soil Pollution* **85**, 25–36.

Harvey, L. D.: 1993, 'Tackling Urban CO_2 Emissions in Toronto', *Environment* **35** (7), 16–20, 38–44.

Hewittt, K.: 1997, *Regions of Risk: A Geographical Introduction to Disasters*, Longman, New York.
Holdridge, L. R.: 1967, *Life Zone Ecology*, Tropical Science Center, San Jose, Costa Rica.
Holling, C. S.: 1992, 'Cross-Scale Morphology, Geometry and Dynamics of Ecosystems', *Ecol. Monographs* **62**, 447–502.
Holling, C. S.: 1995, 'What Barriers? What Bridges?', in Gunderson, L. H., Holling, C. S., and Light, S. S. (eds.), *Barriers and Bridges to the Renewal of Ecosystems and Institutions*, Columbia University Press, New York, pp. 3–34.
Houghton, J. T. et al.: 1996, *The Science of Climate Change*, Report of Working Group I to the Second Assessment Report of IPCC, Cambridge University Press, Cambridge.
ICLEI: 1996a, 'Urban Greenhouse Gas Inventories and Emission Reduction Assessment in Canada', ICLEI and Torrie Smith Associates, Ottawa.
ICLEI: 1996b, 'Ottawa Corporate Challenge Greenhouse Gas Reporting System', Torrie Smith Associates and ICLEI, Ottawa.
IPCC (Intergovernmental Panel on Climate Change, Organization for Economic Cooperation and Development): 1992, *National Inventories of Net Greenhouse Gas Emissions: IPCC Guidelines for Preparation and Reporting*, OECD, Paris, IPCC: 1995.
Jenkins, G. S. and Barron, E. J.: 1996, 'Global Climate Model and Coupled Regional Climate Model Simulations Over the Eastern United States', *Global Planet. Change* **15**, 3–32.
Karl, T. R. and Riebsame, W. E.: 1984, 'The Identification of 10-to 20-year Climate Fluctuations in the Contiguous United States', *J. Clim. Appl. Meteor.* **23**, 950–966.
Karl, T. R. and Riebsame, W. E.: 1989, 'The Impact of Decadal Fluctuations in Mean Precipitation and Temperature on Runoff: A Sensitivity Study over the United States', *Clim. Change* **15**, 423–447.
Kasperson, Roger E., Kates, Robert W., and Hohenemser, Christoph: 1985, 'Hazard Management', in Kates, Robert W., Hohenemser, Christoph, and Kasperson, Jeanne X. (eds.), *Perilous Progress: Managing the Hazards of Technology*, Westview Press, Boulder, CO, pp. 43–66.
Kasperson, J. X., Kasperson, R. E., and Turner, II., B. L. (eds.): 1995, *Regions at Risk: Comparisons of Threatened Environments*, United Nations University, Tokyo.
Kates, Robert W. and Haarmann, Viola: 1992, 'Where the Poor Live: Are the Assumptions Correct?', *Environment* **34** (4), 4–11, 25–28.
Kempton, W.: 1991, 'Lay Perspectives on Global Climate Change', *Global Environ. Change* **1**, 183–208.
Kempton, W., Boster, J. S., and Hartley, J. A.: 1995, *Environmental Values in American Culture*, MIT Press, Cambridge, MA.
Knight, C. G. et al.: 1998, *A Framework for Integrated Regional Assessment of Global Climate Change*, Center for Integrated Regional Assessment, Pennsylvania State University, University Park, PA.
Levin, S. A.: 1992, 'The Problem of Pattern and Scale in Ecology', *Ecology* **73**, 1943–1967.
Liverman, D.: 1992, 'The Regional Impact of Global Warming in Mexico: Uncertainty, Vulnerability, and Response', in Schmandt, J. and Clarkson, J. (eds.), *The Regions and Global Warming*, Oxford University Press, New York.
Manne, A. and Richels, R.: 1990, 'CO_2 Emission Limits: An Economic Cost Analysis for the U.S.A.', *Energy J.* **11**.
Meyer, W. B., Gregory, D., Turner II, B. L., and McDowell, P. F.: 1992, 'The Local-Global Continuum', in Abler, R. F., Marcus, M. G., and Olson, J. M. (eds.), *Geography's Inner Worlds: Pervasive Themes in Contemporary American Geography*, Rutgers University Press, New Brunswick, pp. 255–279.
O'Riordan, T., Cooper, C., Jordan, A., Rayner, S., Richards, K., Runci, P., and Yoffe, S.: 1998, 'Institutional Frameworks for Political Action', in *Human Choice and Climate Change*, v.1: The Societal Framework, Battelle Press, Columbus, OH, pp. 345–439.
Palm, R.: 1990, *Natural Hazards: An Integrated Framework for Research and Policy*, Johns Hopkins, Baltimore.

Pan, Y. et al.: 1998, ‘Modeled Responses of Terrestrial Ecosystems to Elevated Atmospheric CO_2’, *Oecologia* **114**, 389–404.

Parson, E. A.: 1996, ‘Three Dilemmas in the Integrated Assessment of Climatic Change’, *Clim. Change* **34**, 315–326.

Pitelka, L.: 1997, ‘Plant Migration and Climate Change’, *Amer. Sci.* **85**, 464–473.

Rediscovering Geography Committee, National Research Council: 1997, *Rediscovering Geography New Relevance for Science and Society*, National Academy Press, Washington.

Root, T. L. and Schneider, S. H.: 1995, ‘Ecology and Climate: Research Strategies and Implications’, *Science* **269**, 334–341.

Rosenberg, N. J. (ed.): 1993, *Towards an Integrated Impact Assessment of Climate Change: The MINK Study*, Kluwer Academic Publishers, Dordrecht.

Rosenzweig, C. and Parry, Martin L.: 1994, ‘Potential Impact of Climate Change on World Food Supply’, *Nature* **367**, 133–138.

Rosenzweig, C. M., Parry, M. L., and Fischer, G.: 1995, ‘World Food Supply’, in Strzepek, K. M. and Smith, J. B. (eds.), *As Climate Changes: International Impacts and Implications*, Cambridge University, Cambridge, pp. 27–56.

Rothman and Robinson, J.: 1997, ‘Growing Pains: A Conceptual Framework for Considering Integrated Assessments’, *Environ. Monitor. Assess.* **46**, 23–43.

Sampath, R. K. and Young, R. A.: 1990, *Social, Economic, and Institutional Issues in Third World Irrigation Management*, Westview Press, Boulder, CO.

Schipper, L., Ting, M., Krushch, M., Unander, F., Monahan, P., and Golove, W.: 1996, *The Evolution of Carbon Dioxide Emissions from Energy Use in Industrialized Countries: An End-Use Analysis*, LBL 38574, Lawrence Berkeley National Laboratory, August.

Schneider, S. H., and Root, T. L.: 1996, ‘Ecological Implications of Climate Change Will Include Surprises’, *Biodivers. Conserv.* **5**, 1109–1119.

Sellers, P. J. et al.: 1997, ‘Modeling the Exchanges of Energy, Water, and Carbon Between Continents and the Atmosphere’, *Science* **275**, 502–509.

Toth, F. L.: 1995, ‘Practice and Progress in Integrated Assessments of Climate Change’, *Energy Pol.* **23**, 253–267.

Townsend, R. M.: 1995, ‘Consumption Insurance: An Evaluation of Risk-Bearing Systems in Low-Income Economies’, *J. Econ. Perspect.* **9**, 83–102.

Turner II, B. L., Hyden, Goran, and Kates, Robert W. (eds.): 1993, *Population Growth and Agricultural Change in Africa*, University Press of Florida, Gainesville, FL.

Turner II, B. L., Kasperson, R. E., Meyer, W. B., Dow, K. M., Golding, D., Kasperson, J. X., Mitchell, R. C., and Ratick, S. J.: 1990, ‘Two Types of Global Environmental Change: Definitional and Spatial Scale Issues in Their Human Dimensions’, *Global Environ. Change* **1**, 14–22.

Turner II, B. L., Moss, R., and Skole, D.: 1993, *Relating Land Use and Global Land-Cover Change*, IGBP Report #24/HDP Report #5, International Geosphere-Biosphere Program, Stockholm.

Turner II, B. L., Skole, D., Sanderson, S., Fischer, G., Fresco, L., and Leemans, R.: 1995, *Land Use and Land-Cover Change: Science/Research Plan*, IGBP Report #35/HDP Report #7, International Geosphere-Biosphere Program, Stockholm.

Turner, M. G. et al.: 1993, ‘A Revised Concept of Landscape Equilibrium’, *Landscape Ecol.* **8**, 213–227.

Turner, R. S. and O’Hara, F. M.: 1995, *Integrated Assessment: Characterizing Key Policy Issues*, Center for Global Environmental Studies, Oak Ridge National Laboratory.

United States Department of Agriculture, World Agricultural Outlook Board: 1987, *Major World Crop Areas and Climatic Profiles*, USDA Agriculture Handbook No. 664, USDA, Washington D.C.

USGCRP (U.S. Global Change Research Program): 1997, *Our Changing Planet*, The FY 1998 U.S. Global Change Research Program, *An Investment in Science for the Nation’s Future: A Report by the Subcommittee on Global Change Research*, Committee on Environmental and Natural

Resources Research of the National Science and Technology Council, A Supplement to the President's Fiscal Year 1998 Budget, Washington.

Watson, R. T., Zinyowera, M. C., and Moss, R. H.: 1996, *Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses*, Report of Working Group II to the Second Assessment Report of IPCC, Cambridge University Press, Cambridge.

Watson, R. T. et al. (eds.): 1998, *The Regional Impacts of Climate Change: An Assessment of Vulnerability*, Cambridge University Press, Cambridge.

Wilbanks, T. J.: 1984, 'Scale and the Acceptability of Nuclear Energy', in Pasqueletti, M. and Pijawka, K. D. (eds.), *Nuclear Power: Assessing and Managing Hazardous Technology*, Westview, Boulder, CO, pp. 9–50.

Wilbanks, T. J.: 1994, '"Sustainable Development" in Geographic Context', *Ann. Assoc. Amer. Geogr.* **84**, 541–557.

White, G. F. (ed.): 1974, *Natural Hazards: Local, National, Global*, Oxford University Press, New York.

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