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Geographic Scaling Issues in Integrated Assessments of Climate Change

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ABSTRACT

Geographic scale matters in integrated assessments of global climate change issues, but incorporating a variety of scales and cross-scale dynamics in integrated assessment modeling requires confronting a number of conceptual and operational challenges, including upscaling, downscaling, tracing out cross-scale relationships, and multi-scale synthesis.

Keywords: scale, multi-scale analysis, cross-scale dynamics, integrated assessment, place-based analysis, nature-society integration, sustainability science.

1. INTRODUCTION

If top-down, large-scale integrated assessments of global climate change issues were all we need – sufficient to answer most of the important intellectual and practical questions about climate change impacts and responses – then scaling would not be an important enough topic to justify focusing on associated issues. We are learning, however, that answering such questions often requires attention to local scales as well as global, despite very serious operational complications in figuring out how to integrate local-scale analysis into comprehensive integrated assessment modeling.

Recognizing that we are in some respects nosing into territory that, if not entirely new, is still early in a serious exploration process, this paper first reviews how *geographic* scale matters in integrated assessments of global climate change issues. Next, it looks at operational issues in incorporating a variety of scales and cross-scale dynamics in integrated assessment modeling (overlapping several of the other papers prepared for the workshop). It concludes with some suggestions for research to improve our capabilities in dealing with macro-microscale interactions in global change processes.

The intent here is not to dig into a few particular scaling issues in depth but to sketch the landscape of scale-related issues as a contribution to the general workshop discussion, reporting a not entirely integrated assemblage of recent experience that may have some bearing on scaling issues in integrated assessment.

2. HOW SCALE MATTERS

Our understanding about how scale matters is grounded in a number of basic concepts; it is increasingly informed by ongoing integrated assessment activities; and it can be illustrated by several of these activities.

2.1. Basic Concepts

Understanding relationships between macroscale and microscale processes and phenomena is one of the ‘‘grand queries’’ of science [1], and this great intellectual challenge extends beyond geographic scale alone. Clearly, temporal scale raises equally important issues – i.e., between the short term and the long term – and geographic scale and temporal scale are often related in processes of interest; and organizational scale can also be significant in ways not entirely captured by spatial or temporal scale [2, 3].

Considering geographic or spatial scale in this paper, our thinking is generally shaped by several basic concepts that are not always recognized explicitly. For example, we tend to take the following notions as underlying premises:

- When arrayed along a scale continuum from very small to very large, most processes of interest establish a number of dominant frequencies; they show a kind of lumpiness, organizing themselves more characteristically at some

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scales than others (see, for instance, Klemes [4] and Holling [5]). Recognizing this lumpiness, we can concentrate on the scales that are related to particular levels of system activity – e.g., family, neighborhood, city, region, and country – and at any particular level subdivide space into a mosaic of "regions" in order to simplify the search for understanding.

- In many (perhaps most) cases, smaller scale mosaics are nested within larger-scale mosaics; therefore we can often think in terms of spatial hierarchies [5].
- As we look across mosaics at different levels of scale and spatial detail, the importance of cross-border linkages increases as the scale shrinks. This generalization clearly applies to external linkages at the particular scale of interest (e.g., multipliers in regional economics). It is not so clear that the generalization applies to the importance of *cross-scale* linkages: more important at small scales than large? Perhaps not: see below.
- Place is more than an intellectual and social construct; it is a real context for communication, exchange, and decision-making. More than a decade of research by "post-modernist" scholars has established that place has meaning for local empowerment, directly related to equity, and indeed for personal happiness in the face of space-time compression (e.g., Harvey [6], Smith [7], NAS [8]). Scale is not just an operational abstraction. It has meaning for people and processes, related to forms of social organization.

It is tempting, of course, to speculate about how many generalizations about macro-microscale relationships pertaining to geographic scale might apply to other kinds of scale as well. Consider, for instance, the four concepts above as they might apply to functional scale.

Based partly on such concepts, it has been suggested that geographic scale matters in seeking an integrated understanding of global change processes and that understanding linkages between scales is an important part of the search for knowledge [9, 10]. Several of the reasons have to do with how the world works. First of all, the forces that drive environmental systems arise from different domains of nature and society. For example, Clark has shown that distinctive systems imbedded in global change processes operate at different geographic and temporal scales [11]. Within this universe of different domains, local and regional domains relate to global ones in two general ways: systemic and cumulative [12]. Systemic changes involve fundamental changes in the functioning of a global system, such as effects of emissions of ozone-depleting gases on the stratosphere, which may be triggered by local actions (and certainly may affect them) but which transcend simple additive relationships at a global scale. Cumulative changes result from an accumulation of localized changes, such as groundwater depletion or species extinction; the resulting systemic changes are not global, although their effects may have global significance. A second reason that scale can matter is that the scale of *agency* – the direct causation of actions – is often intrinsically localized, while at the same time such agency takes place in the context of *structure*: a set of institutions and other regularized, often formal relationships whose scale is regional, national, or global. Land use decisions are a familiar example. This kind of local-global linkage is especially important where environmental impact mitigation and adaptation actions are concerned, analogous to hazards behavior. A third reason that scale can matter is that the driving forces behind environmental change involve interactions of processes at different locations and areal extents and different time scales, with varying effects related to geographical and temporal proximity and structure. Looking only at a local scale can miss some of these interactions, as can looking only at a global scale. For instance, geographers have shown that processes of change involve patterns of spatial diffusion that can be generalized, and ecological modelers such as Holling have found that managed biomes are characterized by landscapes with lumpy geometries and lumpy temporal frequencies related to the size and speed of process interactions, shaped by the fact that processes operating at different scales tend to show faster or slower dynamics [13].

Several additional reasons have to do with how we learn about the world. One of the strongest is the argument that complex relations among environmental, economic, and social processes that underlie environmental systems are too complex to unravel at any scale beyond the local. A second reason is that a portfolio of observations at a detailed scale is almost certain to contain more variance than observations at a very general scale, and the greater variety of observed processes and relationships at a more local scale can be an opportunity for greater learning about the substantive questions being asked (e.g., Fig. 1). In other words, variance often contains information rather than "noise." A third

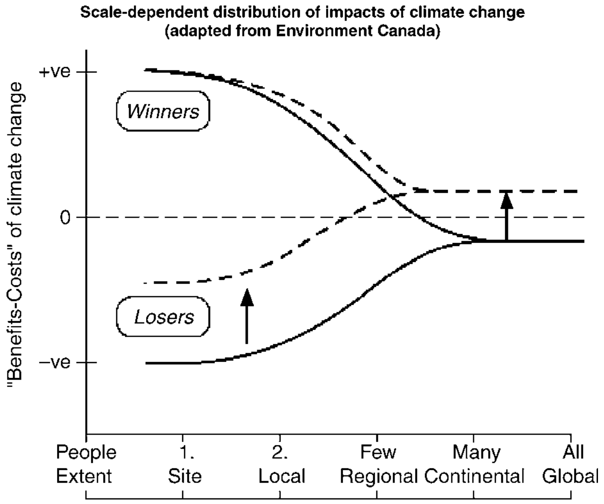


Fig. 1. Scale-dependent distribution of impacts of climate change (adapted from Environment Canada [20]).

reason is that research experience in a variety of fields tells us that researchers looking at a particular issue top-down can come to dramatically different conclusions from researchers looking at that very same issue bottom-up. The scale embodied in the perspective can frame the investigation and shape the results, which suggests that full learning requires attention at a variety of scales. As one example, Openshaw and Taylor [14] have demonstrated that simply changing the scale at which data are gathered can change the correlation between variables virtually from $+1$ to -1.

These reasons, of course, do not mean that global-local linkages are salient for every question being asked about global change. What they suggest is more modest: that examinations of such changes should normally take time to consider linkages between different scales, geographical and temporal, and whether or not those linkages might be important to the questions at hand.

2.2. Findings to Date

Quite a number of recent assessments and studies have offered learning experiences about how geographic scale matters in trying to understand global change and its impacts. Examples from a U.S. perspective include the ‘‘Global Change in Local Places’’ (GCLP) project funded by NASA through the Association of American Geographers, 1996–2000 [1, 9]; the first U.S. National Assessment of Possible Consequences of Climate Variability and Change (NACC), 1997–2000 [15]; the recent U.S. National Academy of Sciences/National Research Council report on pathways for a ‘‘sustainability transition’’ [16]; and a variety of other activities, including the ongoing work of the Global Environmental Assessment Project (GEA) at Harvard University (e.g., Clark and Dickson [17]), the Long-Term Ecological Research (LTER) network sponsored by the National Science Foundation in the U.S. (e.g., Redman et al. [18]), and the Land-Use/Land Cover Change project jointly sponsored by the IGBP and the International Human Dimensions Programme.

Learning from these and other recent research experiences – often related to and drawn from a variety of disciplinary literatures – one can offer some tentative findings about how geographic scale matters, stated as propositions as a basis for discussion.

Even (especially?) in an era of globalization, attention to the local end of the spectrum is critically important.

- Integrative research on complex sustainability issues is best carried out in a place-based context. According to recent reviews of the development of earth system science and global change research in the U.S. [19], the most fundamental change in the past decade has been a recognition that integrative research must be down-scaled and place-focused. This conclusion is reported as an empirically-based finding by both the NAS/NRC sustainability transition report and the U.S. national climate change assessment.
- Many important global change issues are inherently regional/local rather than global or national in scale. The most salient example is vulnerabilities to *impacts* of global or national-scale processes. Clearly, the interest in bottom-up perspectives, or at least in down-scaling top-down perspectives, has grown as the emphasis in global change research has shifted from better understanding atmospheric dynamics toward better understanding impacts of climate change. Figure 1, for example, summarizes a key finding from the Canadian climate change assessment [20], that variations in net benefits from climate change appear much more clearly at more detailed scales.
- Local-scale attention is essential for implementing sustainability actions. It bounds the realistic and the possible in sustainability actions, identifies a wider range of opportunities for action, and assists in establishing effective larger-scale structures [1]. In other words, it helps to make sustainability more achievable. In fact, GCLP has noted a number of undesirable unintended *local* consequences in the U.S. of one-size-fits-all policy actions at a *national* scale.
- Local-scale investigation facilitates assessment as a *social* process. It encourages and facilitates exchanges of information and understanding between investigators and stakeholders, not just disembodied organizational representatives of stakeholders, which connects the issues with local empowerment, constituency-building, and other aspects of democratic decision-making at a variety of scales.

Sustainability science needs to be sensitive to *multiple* scales rather than focused on a single scale.

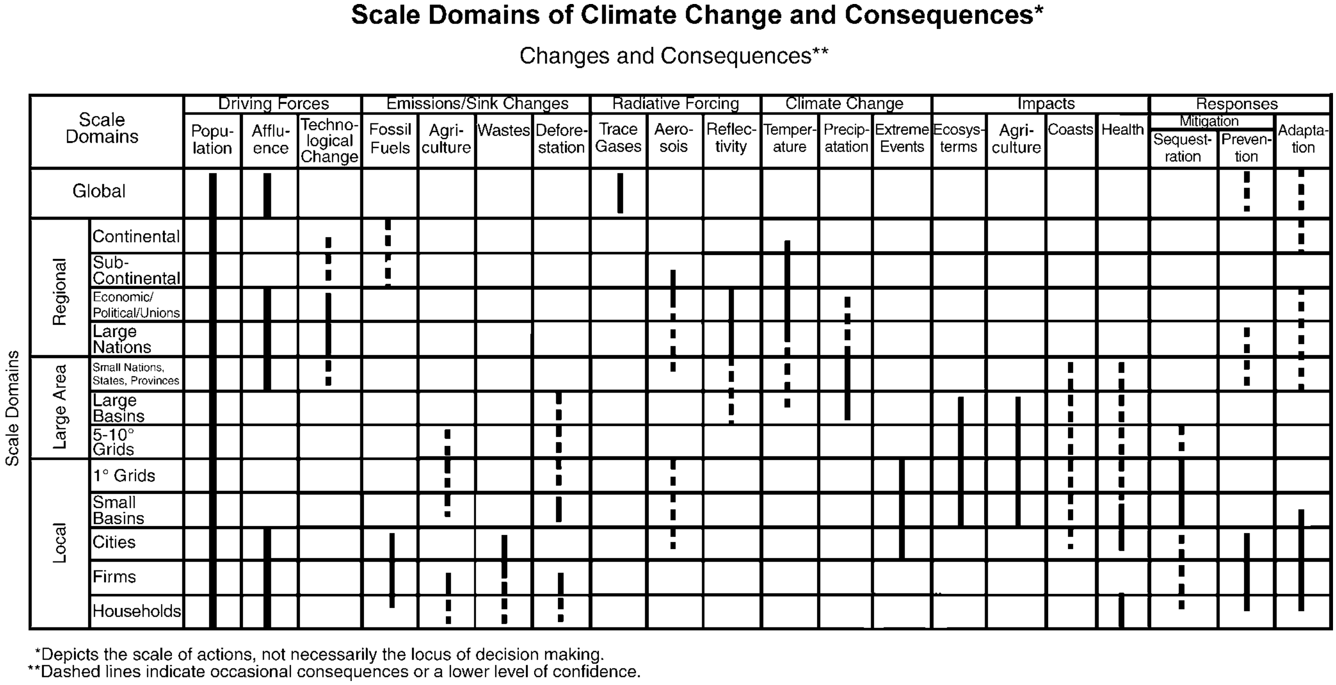
- Selection of a single scale can frame an investigation too narrowly. Whether the scale is global or local, a single scale of attention tends to focus on issues, processes, data, and theories associated with that scale, when a full, integrated understanding calls for attention to perspectives associated with other scales as well [21] (also see Gallegher and Appenzeller [22]). Moreover, research in a wide variety of fields has shown that the results of analysis can be scale-dependent (e.g., Rosswell et al. [23] and Joao [24]) and that, indeed, the concept of ‘‘equilibrium’’ is inherently scale-dependent in complex systems [25]. Schneider has suggested that different scales may be amenable to different research questions related to a common line of inquiry: e.g., larger scales to seek larger associations, smaller scales to ask ‘‘why.’’
- Phenomena, processes, structures, technologies, and stresses operate at different scales. This means that observations of processes at larger scales may not reveal causal mechanisms needed either to forecast system behavior reliably or to determine appropriate actions (e.g., Jarvis [26]). Conversely, observations at smaller

scales may not reveal processes responsible for larger-scale patterns – nor the possibility of "emergent properties". It seems especially likely that scale is related to uncertainty and surprises, a central issue in considering climate change. A familiar case in integrated assessment is waste emission and disposal, which often involves processes at multiple scales: from local point-source emission streams to regional emission plumes to national regulatory structures. Moreover, the scale of such factors may be subject to change through time, as in the case of the scale of agricultural production in the U.S. Phillips [27] suggests that for any divergent landscape in earth surface systems, there are at least three scale ranges where fundamental system behavior differs.

- A particular scale may be more or less important at different points on a single cause-consequence continuum. Figure 2 illustrates such a continuum schematically, suggesting that for global climate change processes most emissions and many responses are relatively local, while radiative forcing is clearly global in scale.
- No single scale is ideal for broad-based investigation. The GCLP project found that arbitrary use of a one degree scale has no intrinsic value (see below), and the U.S. national climate change assessment found that there was no ideal scale for investigating regional impact issues (e.g., more detailed scales were better for stakeholder interaction but demanding in terms of funding, local expertise, and management requirements). In nearly every case, valid arguments can be made for either larger or smaller scales, or for boundary modifications to include or exclude activities of interest that have particular weight and might therefore have a significant impact on general findings. A particular problem with using a latitude/longitude-oriented scale for local studies – whether one degree, half a degree, or some other grid size – is that the scale is unlikely to approximate the scale and boundaries of any significant decision-making unit, although "gridded" approaches are common in ecology and certain other fields. As a general rule, the GCLP experience indicates that, if the intent of a study is to inform decision-making, there is merit in relating the scale of the study to the scale of decision-making units appropriate to the issues of greatest interest (also see Cash and Moser [28]).

Improving the understanding of scale dimensions of sustainability calls for certain kinds of research strategies.

- Monitoring and data-gathering are needed at multiple scales, including careful attention to appropriate indicators. NACC, the sustainability transition study, GCLP, LTER, and other recent studies have concluded that our existing monitoring systems are inadequate for understanding multiple stresses at multiple scales. Building an effective knowledge base for comprehensive integrated assessment modeling requires fully-integrated observational systems, monitoring multiple variables at multiple scales. In the meantime, the sustainability transition study found no consensus on the appropriateness of existing indicators as a basis for such monitoring approaches [16].


Scale Domains of Climate Change and Consequences*

Changes and Consequences**

*Depicts the scale of actions, not necessarily the locus of decision making.
**Dashed lines indicate occasional consequences or a lower level of confidence.

Fig. 2. Scale domains of climate change and cosequences (Source: Kates et al. [1]).

- "Protocols" for local-scale studies would improve prospects for aggregating their results. One of the most common reservations about bottom-up approaches to local-scale studies is that they usually take the form of case studies that can be exceedingly difficult to aggregate. GCLP suggests that the prospects that local area studies of global change, conducted by different people at different sites, can produce comparable results would be improved by encouraging individual studies to ask similar questions, generate data in similar categories based on similar techniques for measurement or estimation, and make data available in similar formats. Guidelines for such a shared approach can be termed a "protocol." Unfortunately, at least in the U.S., existing protocols created for analyses at a regional or national scale, such as the U.S. Environmental Protection Agency's state workbook, are not readily transferable to a local scale. For instance, they often call for data not available at the scales of smaller area units. What is needed, GCLP indicates, is a "process protocol" which describes a *process* for conducting local area studies that can be followed by study teams with varying resources and other constraints.
- Using local experts as "gate-keepers" helps in eliciting local knowledge and communicating with local stakeholders. A relatively robust finding in studies of environmental assessment experiences worldwide is that the results of assessments are much more likely to be put to use in local areas if they are channeled through local experts (i.e., the right-hand curve in Fig. 3). GCLP found the same thing to be true in the opposite direction as well. Local experts are uniquely suited to assist in accessing local knowledge, because they are repositories of so much of that knowledge and because their local contact networks – often strengthened by the presence of former students in local institutions – usually embrace the most important of the local information infrastructures.
- Effective approaches are needed for integrating top-down and bottom-up perspectives. GCLP, NACC, and other studies indicate that tools for integrating perspectives across spatial scales are still limited, although this is an area of research which is showing considerable creative activity (see "Operational Issues" below). From a modeling point of view, of course, a central issue is handling such integration in scientifically-valid ways that permit replication, along with evaluations of conditionalities and uncertainties.

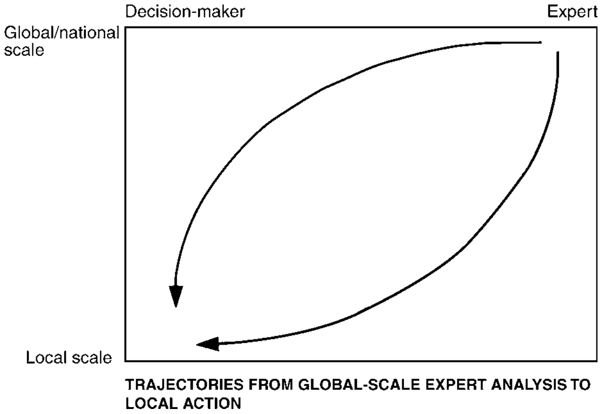


Fig. 3. Trajectories from global-scale expert analysis to local action.

2.3. Elements of a Coherent Story Line About How Scale Matters

If "all science is storytelling," as we hear from our social theorist colleagues, we should try to turn these individual findings into a coherent story of how the macroscale and the microscale are connected in global change processes. Unsurprisingly, in trying to cover a broad continuum of geographic scales such a story is necessarily immersed in "on the one hand…; on the other hand…" perspectives. For example, we are coming to understand that on the one hand sustainability can only be operationalized for particular places, but on the other hand every place is affected by others. We know that many key actions are local, but most key actions are shaped by broader structures. We know that many of the strongest *driving forces* are trans-local, but we also know that (a) many of the *impacts* are relatively local and that (b) in a democratic society many of the *responses* are shaped by a cumulation of local concerns.

The beginning of a coherent story, capturing these kinds of complications, is depicted schematically in Figure 4. Shaped themselves by external driving forces, local actions have systemic or cumulative impacts on processes that operate at global, national, or large-regional scale. If those impacts are judged to be undesirable or risky, there may be institutional responses at those larger scales, leading to structures designed to assure sustainability. That process, in turn, is shaped – at least in democratic societies – by support and/or opposition at local scales. The structures then provide enablement, constraints, and/or incentives to stimulate adaptive behavior at a local scale, leading to changes in local processes and actions; and the cycle continues.

This picture is only offered as a basis for discussion, but it is evocative enough to suggest certain implications. For example, it suggests that actions aimed at driving forces need a larger-scale context, while actions aimed at impact reduction/adaptation need a smaller-scale context. It suggests that sustainability is grounded in linkages between different scales of concern. Taking this logic one more step, one might suggest that an over-emphasis on top-down forces can threaten sustainability by provoking backlash from disenfranchised local stakeholders, by being insensitive to local context, and by failing to empower local creativity. At the same time, an over-emphasis on bottom-up forces can also threaten sustainability by missing the importance of larger-scale driving forces, by being insensitive

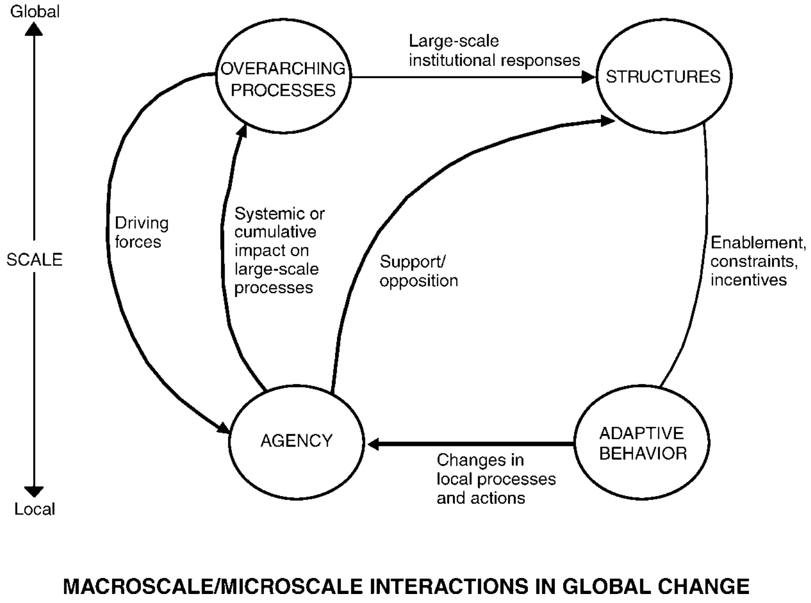


Fig. 4. Macroscale/microscale interactions in global change (Source: Kates et al. [1]).

to larger-scale issues (temporal as well as spatial), and by being uninformed about linkages between places and scales. This indicates a need for balance and harmony in a multiscale, interrelated system for assessment and action, when in so many cases philosophies, processes, structures, and knowledge bases are lacking to assure such a balance.

An illustrative example: I

One example of an effort to explore such interactions is the Global Change in Local Places research project of the Association of American Geographers, funded by what was at the outset NASA's Mission to Planet Earth program. This project was focused on the challenge of linking scales in understanding global change. Conceived and designed in 1994 and 1995, it was concerned with three aspects of global change research at that time (Fig. 5):

- Changes in human activities that alter GHG emissions and uptakes and surface albedo
- Driving forces for these changes
- Capacities of localities to mitigate and adapt to changes

If the project had been designed a few years later, of course, it would have included a fourth aspect as well: local impacts of global change. At the time, however, the capacity to forecast climate change impacts at a regional scale was still quite limited, roughly five degrees latitude-longitude; and a climate change impact dimension of a much more localized study appeared infeasible.

Initially, GCLP included three local study areas defined at a scale of approximately one degree (equatorial) latitude-longitude: the Blue Ridge – Piedmont area of Western North Carolina; a portion of the Central Great Plains in Southwestern Kansas, underlain by the Ogallala aquifer; and a portion of the traditional U.S. manufacturing belt in Northwestern Ohio. A fourth study area was added later – a six-county area in the vicinity of Pennsylvania State University in Central Pennsylvania - taking advantage of a strong overlap between the aims and approaches of GCLP and research activities already underway in Penn State's Center for Integrated Regional Assessment.

As GCLP proceeded, it was linked with a number of other activities also concerned with macroscale-microscale interactions in global change processes, such as NACC, the

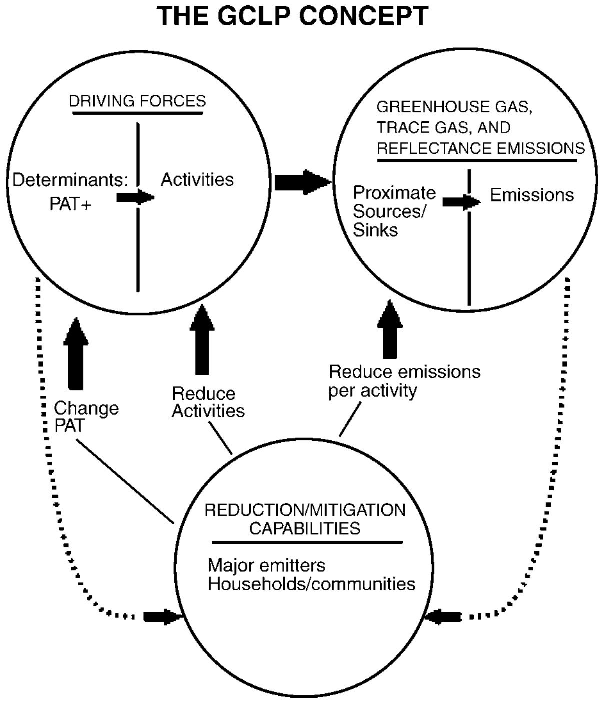


Fig. 5. The GCLP concept (Source: Wilbanks and Kates [9]).

NAS/NRC sustainability transition study, GEA, and the evolution of the LTER concept in the U.S. In particular, it joined forces with the Cities for Climate Protection (CCP) program of the International Council for Local Environmental Initiatives (ICLEI), which had developed an Internet-based approach for assessing potentials for GHG emission reductions by cities and metropolitan areas that is now in use in more than 300 cities worldwide [29].

Findings from GCLP are still emerging, such as its analysis of potentials for the local study areas to meet hypothetical emission reduction targets in 2020; but some of the tentative findings may be of interest. Simply stated, the project found that local knowledge is important, albeit not for everything. The familiar slogan "*Think globally and act locally*" is inadequate because global or even national knowledge averages together too many distinctive local trajectories of action and change, missing potential response opportunities and making local actions more difficult. Local knowledge, however, is also inadequate, since for the most part the locus of decisions related to climate change responses is not locally-based.

In general, GCLP found that local greenhouse gas (GHG) emissions are not greatly different from national patterns; the importance of a local scale of attention lies not in the big picture of emissions but in the details, and these details are especially important in understanding both trends through time and in identifying opportunities for local action. In the four GCLP sites, GHG emission details mainly reflected five factors: the location and fuel use of electricity generation, the degree to which the local economy has a natural resource orientation, the dynamics of local economic development, changes in technology through time, and growth rates in the number of households. Driving these factors are such underlying processes as consumer demand, regulation, energy supply and price, economic organization, and social organization.

Within these contexts, the potential for local action to reduce GHG emissions is considerable, if: there is a conviction based on the local context that such action is a good idea, there is some local control over significant emission decisions, and the locality has access to technological and institutional means to make a difference. On the other hand, the GCLP local area studies found that the current institutional framework in the U.S. does not motivate and facilitate local action, and the portfolio of technology opportunities is often a poor fit with local emission abatement potentials.

An illustrative example: II

A very different kind of example is a current research project at the Oak Ridge National Laboratory (ORNL), supported by internal discretionary research funds. Initiated in October 1999, this three-year project – labeled "Improving the Science Base for Evaluating Energy and Environmental Alternatives" – is intended to improve the tools available for comparing benefits and costs of global climate change impact *avoidance* (i.e., GHG emission abatement) with benefits and costs of global climate change impact *adaptation.*

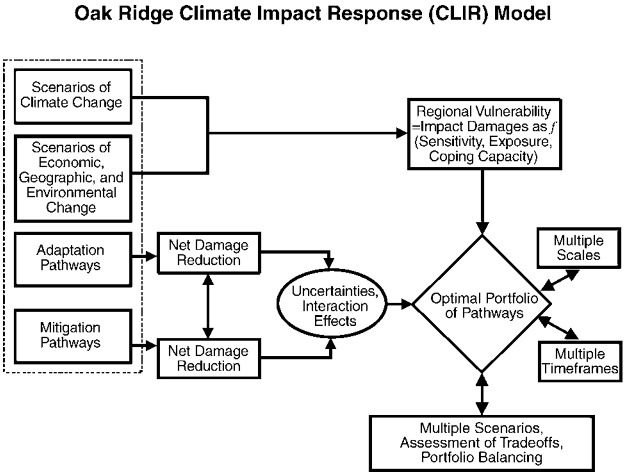


Fig. 6. Oak Ridge Climate Impact Response (CLIR) Model (Source: Wilbanks et al. [31]).

Essentially, this project includes three main components: (1) developing and characterizing a taxonomy of adaptation pathways as a basis for comparison with available characterizations of mitigation pathways (most notably US DOE [30]); (2) improving the science base for pathway analysis, emphasizing macroscale/microscale integration and *portfolio* optimization (rather than optimization in terms of individual pathways based on a conventional supply curve); and (3) tool development for comparative analysis (Fig. 6 is a preliminary indication of the general structure of the tool).

Even though the project is still in its early stages, scaling issues have already emerged as central to the activity. For instance (as a broad generalization), the benefits of GHG emission abatement are spread globally through their contributions to reducing the rate of increase in carbon concentrations in the earth's atmosphere. Benefits of most adaptation pathways, on the other hand, tend to be associated with regionally or locally specific impact vulnerabilities, and therefore to generate benefits at a relatively local scale. This suggests that the results of a comparison of avoidance and adaptation pathways will depend on the scale of the analysis: a macroscale favoring avoidance actions and a microscale favoring adaptation actions. To the degree that climate change policy depends on intra-country political processes and thus net benefits at a regional or local scale, this may hint that adaptation will be favored by some of the key national players in global change policymaking in years ahead. Such a possibility, of course, is one reason for seeking an analytical approach which will produce an optimal course of action that is portfolio-oriented, including a combination for both adaptation and avoidance pathways. Incidentally, it also appears that the *temporal* scale of avoidance benefits and costs is longer, perhaps considerably longer, than the temporal scale of adaptation benefits and costs. Here again, there is a need to integrate both macroscale and microscale perspectives.

3. OPERATIONAL ISSUES

As an operational question, determining how to incorporate macroscale and microscale information and perspectives into integrated assessment models depends on the conceptual approach that is adopted, but it (ideally) involves two fundamental dimensions: incorporating information from multiple scales and incorporating information about interactions between scales.

3.1. The Principal Alternatives

Although the conceptual approaches that can be considered are probably as numerous as the investigators using them, at a very general level they can be categorized in one of two ways: (a) convergence at a single "meso" or regional scale or (b) seeking a multi-scale or meta-scale synthesis of insights from a number of scales. A third alternative, of course, is to continue to model at a global scale but to make an effort to aggregate data and process understandings from smaller scales [32]. Perhaps convergence approaches imply a perspective that process representations can be considered seamless across scales, while multi-scale or meta-scale perspectives imply a rejection of that point of view [33].

3.1.1. Convergence at a Single "Meso" or Regional Scale

The most common approach is to integrate scale-related information at an intermediate scale as a way to provide a transition among various scales, either by converting data to a common geographic metric, by solving separately at different scales and then iterating to convergence, or by relying on empirical information about the scale of particular regional processes of interest:

- Conversion to a common metric

  One common approach, possibly the most-often used analytical strategy at present in climate change impact/response studies, is to down-scale information about global processes (such as global climate change) and up-scale information about local processes (such as agricultural production) to meet at an intermediate scale [34]. The current frontier appears to be a scale of one-half degree latitude-longitude, or a cell of about 50 km on a side, with the principal driving factor being limits on the down-scaling of climate change forecasts.

  Generally, the strategy is either to focus on the smallest scale that is feasible with available data sets or to determine the appropriate scale based on statistical analyses. In trying to define the most appropriate scale, one approach has been to try to find the scale at which data related to a particular question show maximum inter-zonal variability and minimum intra-zonal variability. Another identifies the scale, which minimizes statistical error between observed and modeled phenomena [35]. Still another seeks to balance the increased information from finer spatial resolution against the increased difficulty of gathering the information and modeling the processes [36].

  Examples of such work include a variety of efforts by Linda Mearns of the U.S. National Center for Atmospheric Research (NCAR) and others to explore effects of climate variability and change on agriculture in the U.S., especially in the Southeast (e.g., Mearns et al. [37]). Among the challenges noted from this experience is mismatches in the scale resolution of different data sources [38].
- Iterating to convergence

  An alternative is to use different analytical models to derive solutions at different scales and then to iterate back and forth until the results converge. This approach has been widely practiced, at least informally and qualitatively, for much of the past quarter-century. A recent example is incorporated in IIASA's integrated assessment model for examining energy-economy-environment interactions [39]. One component of this modeling structure couples a top-down macroeconomic model, 11R, modified from the Global 2100 model developed by Manne and Richels, with a bottom-up dynamic LP model, MESSAGE III, that selects cost-minimizing technology combinations. The model-linking approach, as described by Wene [40], is based on iterative adjustments of aspects of the two different models until harmonization of their results is achieved.
- Empirical evidence of the scale of regional processes

  Still another approach is to select an intermediate or mesoscale for integrative analysis on the basis of case-by-case empirical evidence and qualitative understandings of the process involved, rather than based on formal modeling conventions or statistical analyses per se (e.g., Hirschboeck [41]). Although this approach can be difficult to capture in formal modeling logic and difficult to replicate precisely, it is both intuitively and intellectually attractive and also relatively easy to explain to external audiences. Many of the most thoughtful and evocative examples of the art of regional integrated assessment in recent years can be included in this category, including the Kasperson, Kasperson, and Turner book on *Regions at Risk* [42] and the focus of the German Advisory Council on Global Change [43] on characteristic "syndromes" that represent the greatest threats to sustainability [44], where the relevant scale is defined by looking in detail at the functions of processes and mechanisms (see chapter 10).

3.1.2. Seeking a Multi-Scale or Meta-Scale Synthesis

Alternatively, one can try to get results from asking the same question at each of several scales and, rather than iterating to convergence on a single answer, preserve the different answers and seek a higher level of understanding that derives insights from all the answers: e.g., to what degree are the answers different across scales? One example of this approach is the Susquehanna River Valley study which has been carried out over a number of years by a multidisciplinary research team at Pennsylvania State University. This team has analyzed such issues as the net cost of a national carbon tax at four different scales, finding strikingly different answers depending on the scale of attention [45]. Another example is a recent study of prospects for adaptation to global climate change in Australian agriculture, including attention to both farm-level decision-making patterns and national scale trends and structures [46]. Yet another example is work in progress at Oxford University which mixes bottom-up and top-down approaches in constructing vulnerability indicators [47].

In essence, this research accepts the results of analysis at each of several scales as all being aspects of a larger truth and looks for broader understandings that embrace and aid in understanding the variety of single-scale answers, usually seeking these understandings through qualitative judgments by assessment experts and, in some cases, stakeholders.

Two examples of methodological conceptions that illustrate this perspective are ‘‘strategic cyclical scaling’’ and ‘‘hierarchical patch dynamics’’ (strategic cyclical scaling [48] will be discussed in greater detail in chapter 9 in this volume). Very briefly, it proposes a continuing cycling between upscaling and downscaling approaches, with each affecting the design of the other; and the early tests of this paradigm have been encouraging.

Hierarchical patch dynamics emerged from several decades of attention to pattern-process relationships in ecology, stimulated by Watt [49]. This approach proceeds from a conception of large-scale ecologies as nested hierarchies of patch mosaics, with overall ecosystem dynamics related to patch changes in time and space but moderated by metastability at a larger scales, not necessarily destabilized by the transient dynamics often characterizing local phenomena [50]. Patch dynamics are normally modeled by analyzing pattern-process relationships at several (or all) levels in the hierarchy, then examining how the findings at the different levels relate to each other (e.g., a trend from less stability at more local scales to more stability at larger scales or a relationship between scale and the speed at which component subsystems operate). In some cases, dynamic simulation modeling is employed to explore such issues as the ‘‘incorporation’’ of instability among hierarchical levels.

3.1.3. Comparing the Two Alternatives

Obviously, neither approach is clearly preferable for every conceivable purpose. Incorporating multiple scales is intellectually satisfying and may in some cases pick up inter-scale differences and interactions missed by regional synthesis, and this approach seems more promising for systems in which some scenarios converge on steady state A while others converge on B or C (Schneider, personal communication). A focus on a single region, however, when that region has some intrinsic meaning in terms of the empirical scale of a key concern or the ability to make decisions and take actions, can enable a firm grounding in reality. The main determinants are likely to be utility, operational feasibility, and the purposes of the assessment.

In several important respects, the two alternatives are in fact similar. Both require some upscaling of more localized data and some downscaling of data and/or forecasts from global and other very large scales. Both are shaped by understandings derived from the general scientific literature (a kind of downscaling in which most upscaling is embedded: Root and Schneider [48]); and both are cognizant of relatively high-visibility findings from localized experience, including the investigators' own life experiences.

In addition, neither alternative necessarily addresses cross-scale dynamics, although neither excludes them. In terms of philosophical orientation, the practice of meta-scale synthesis appears to be more directly concerned with this dimension of integrated assessment.

3.2. The Principal Challenges

The challenges faced in operationalizing these approaches as ways to incorporate scaling into integrated assessment modeling range from conceptual to technical and data-based. As a very broad generalization, it can be suggested that the most fundamental challenges to regional synthesis are data-based, while the most fundamental challenges to meta-scale synthesis are conceptual.

3.2.1. Regional Synthesis

Obviously, operating at a single mesoscale requires some combination of upscaling, downscaling, and integration. One of the richest bodies of research experience in meeting this challenge is Geographic Information System (GIS) research (e.g. Quattrochi and Goodchild [51], NCGIA [52], Turner et al. [53], Turner [54] and, for relationships with simulation modeling: Wilson and Burrough [55]), although the preoccupation of GIS research with integrating spatial patterns is an imperfect fit with the needs of integrated assessment. For instance, the very substantial GIS problem of upscaling line patterns such as rivers and highways for display at a much more general scale is not the sort of thing that worries an integrated assessment modeler. On the other hand, the challenges associated with converting data for areal units into different spatial metrics are similar, and the abler GIS practitioners share a strong interest in process understanding in order to assure that the tool is both substantively valid and socially useful. Another substantial body of experience, of course, is landscape ecology (e.g., Rastetter et al. [56], Turner et al. [57]).

– Upscaling

Many kinds of data pertinent to macroscale issues are gathered at specific points or in small areas, ranging from meteorological observations to crop production to soil samples. In addition, if future research support follows recent conclusions that integrated assessments of complex issues should be place-oriented, often implying a small-regional scale, then building larger-scale understandings from a growing portfolio of more or less localized case studies is an upscaling challenge that will be growing.

Essentially, upscaling is an aggregation challenge, and a very serious technical challenge indeed [58, 59] (see also Curran et al. [60]; Butterfield et al. [61]; Smith et al. [62]). In many cases, data cannot simply be aggregated to estimate larger-scale values, such as regional agricultural production or climate processes. For instance, the data may fail to meet standards for valid sampling, or they may fail to represent stochastic and geographic variability in representing how processes work. As one example, it has been shown that an estimated response to an ‘‘average’’ environment can be a biased predictor of a ‘‘true’’ aggregate response [63]. Or aggregate totals may lose information about variability that is instructive, or the value of the aggregate may be undermined by the fact that processes operate differently at different scales (i.e., ‘‘local’’ is not necessarily micro-global).

The challenge is especially complicated when larger-scale characterizations are being constructed from incomplete local evidence: e.g., from a small number of at least somewhat idiosyncratic case studies (regardless how sound they may be). One such problematic situation is an effort to aggregate estimates of the net economic cost of climate change impacts on small areas in order to arrive at a total global or continental net cost, which has been a subject of discussion in producing the Third Assessment Report of IPCC Working Group II (Impacts, Adaptation, and Vulnerability) [64].

A number of technical alternatives for dealing with statistical problems in upscaling have been outlined by Harvey [58], including distributed point process modeling, parameterization of patch interactions, linking mechanistic models between scales, changing model resolution, and creating new models. Another approach is regional calibration: comparing aggregates of individual records with regional records. Rastetter et al. [56] identify four methods: partial transformations using a statistical expectations operator, moment expansions, partitioning based on spatial autocorrelation, and regional calibration (regarding the use of interpolation to fill gaps in upscaling, see chapter 5).

– Downscaling

Downscaling is equally essential as an aspect of integrated assessment, because so many critical driving forces – e.g., global climate dynamics, global population growth, global economic restructuring, and global technology portfolios – operate at very large scales but shape local realities and choices. In this connection, it goes without saying that the integrated research community recognizes the limitations of top-down paradigms based on global or near-global scale modeling alone [43]. Modelers are moving toward more detailed geographic scales and topical richness, using both numerical (i.e., model-based) and empirical (i.e., data-based) approaches (for one review, see Bass and Brook [65]; for an example of the current state of the art, see Easterling et al. [66]). Challenges include limited data availability at detailed scales (at least without expensive new data-gathering), the increasing complexity of causal relationships as models become more like the real world, challenges of capturing contextual detail to approximate local reality more closely (e.g., incorporating terrain in climate change modeling), and in some cases computational capacity (although advances in computing have reduced this constraint considerably).

An example of the breadth of the current downscaling research enterprise is the range of approaches being applied experimentally in Pennsylvania State University's Susquehanna River basin study (Yarnal, personal communication). Four approaches have been used to date. In one approach, Jenkins and Barron [67] embedded a regional climate model in a global circulation model, showing significant improvements over precipitation projections from the GCM alone. A second approach linked a nested version of a mesoscale meteorological model to a hydrological model system, which simulates basin hydrology at relatively detailed scale [68]. A third approach employed artificial neural network analysis for empirical climate downscaling to investigate cross-scale relationships between large-scale circulation and humidity fields and local precipitation [69]. A fourth approach used more traditional synoptic climatological analysis *to relate* atmospheric dynamics to various scales of basin runoff, showing different characteristic responses for different basin scales [70].

One of the forces encouraging downscaling is an interest in fostering public participation in discussions of issues being addressed by integrated assessment [71]. A frequent discovery in such a process is that, as presently constructed, models do not always produce answers to the questions being asked. This has led to consideration of ‘‘inverse’’ approaches to assessment modeling, beginning with relevant bottom-up questions and working back toward appropriate modeling structures. In this sense, listening to local concerns can help to catalyze a rethinking of how integrated assessment modeling is done.

– Integration

Once all relevant data are converted to a common metric, or an algorithm for iterative convergence is specified, the integration challenge has been greatly simplified – but in some cases perhaps misleadingly so. If the aim is to attain an integrated understanding of processes, simply converting numbers to a common spatial scale does not necessarily assure *conceptual* integration, as contrasted with *computational* integration. In most cases, full integration also involves attention to interactions between processes that operate at different scales, because processes and controls that shape them, and appropriate representations of them, may not be scale-invariant. It often involves bridging between analytical styles, e.g., top-down models and bottom-up case studies, in order to understand the meaning behind the different perspectives imbedded in the source data. In addition, it is often a matter of reconciling differences in process assumptions, theoretical foundations, and perceived standards as to what constitutes the best science, sometimes rooted in different disciplinary traditions.

Further, because different interacting processes may operate at different scales (e.g., between the scale of ecosystems and the scale of governmental units making decisions about them), efforts to incorporate a variety of linkages in a single analysis or action often must confront problems of “scale mismatch” [72, 28]. Among the avenues being investigated are “adaptive” approaches to analysis and assessment, which permit modifications of the scale as more is learned about the relevant processes and their interactions.

What we know is that how integration is done can affect its outcomes. It is at least arguable that in many cases integration incorporates certain values of the modeler – often implicitly, sometimes without the modeler’s full awareness – and that this undermines the supposed objectivity of the process [73]. We also know that the scale at which integration is performed and results are reported can affect uses of the work.

– Addressing cross-scale dynamics

A profound general problem, because so much data collection and analysis occurs at a particular scale, large or small, is that data (and understandings) are often scarce about cross-scale relationships and interactions. The challenge is to simultaneously capture driving and constraining forces at multiple scales and how they relate to each other [74].

Aside from system dynamics types of approaches, the most common strategy is to call upon hierarchy theory [75–77], which assumes that interactions between the dynamics of processes and structures at different scales shape systems at any one scale and that, therefore, hierarchies of scale-related processes define “constraint envelopes” within which systems can operate. Hierarchical perspectives can, however, be applied without necessarily relying on hierarchy theory. An example of a formal statistical approach related to this perspective, concerned with multiscale statistical inference, begins with a set of hierarchically defined partitions and then combines “data likelihoods” at each scale with a Bayesian prior probability structure [78]. One problem, of course, is that cross-scale dynamics may not always fit neatly into hierarchical structures.

Still another possible source of ideas – at least for cross-scale *pattern* dynamics – is the literature on fractal structures [79], which suggests a predictable relationship between the scale of measurement and the measured phenomenon. Whether such relationships might also hold for non-pattern aspects of chaotic system dynamics is not so clear.

A positive recent step has been efforts (e.g., by the U.S. National Science Foundation) to establish richer information infrastructures, especially regarding longitudinal data sets, although – as we all know – assuring continued financial support for really long-term data collection structures is a continuing challenge.

3.2.2. Meta-Scale Synthesis

On one level, it is not too difficult to outline a general approach for utilizing perspectives from multiple scales. Elements of a general strategy would include definition of a question to be answered (e.g., how much may climate change impacts be reduced by autonomous adaptation, or how much is biodiversity likely to be reduced by global climate change); conversion of the questions into operational definitions amenable to quantitative measurement and analysis, consistent with available data; selection of two or more scales, ideally perhaps three or four related to relevant conceptions of hierarchical levels in processes of interest [80], a compromise between an intellectual interest in all levels and resource limitations; calculation of an answer to the question at each of the scales; displaying the set of answers in a format that provides insights about patterns and/or relationships; and derivation of findings from that display, maybe using more or less standardized conventions.

This strategy, however, only fills only a part of the need. It has the clear potential to illuminate differences among scales in functional relationships important in understanding global change, avoiding tunnel vision from looking at such relationships at only one scale. It may not, however, necessarily illuminate interactions between scales. Addressing cross-scale dynamics in integrated assessment seems to call for one of four approaches (or a combination of them): (a) the kind of cyclical analysis proposed by strategic cyclical scaling, with each scale iteration including specific attention to interactions with other scales, (b) use of a methodology that delivers simultaneous solutions of equations representing within-scale and cross-scale relationships, such as system dynamics approaches, (c) finding and adopting a conceptual/theoretical construct that relates the macroscale and microscale processes, such as the patch-dynamics hypothesis and/or hierarchy theory, or (d) stepping out beyond the formal integrated assessment activity to access macroscale-microscale interaction

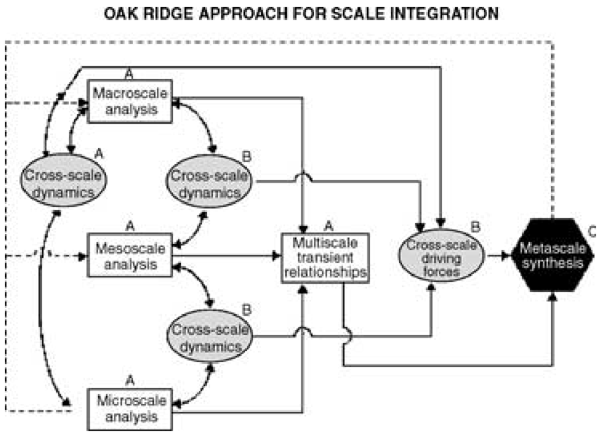


Fig. 7. Oak Ridge approach for scale integration.

understandings from relevant literatures and/or expert judgments, inserting the resulting understandings as additional model specifications, parameters, variables, or uncertainties. One example of a possible integrative approach is outlined conceptually in Figure 7; note the challenge of integrating both multiscale and cross-scale understandings in a single computational system.

For these and less ambitious meta-scale integration goals, three central challenges are worth considering:

– Data availability
  GCLP found that many questions being addressed by research protocols at global, national, or large regional scales cannot be pursued readily at more local scales because of a lack of availability of data at those detailed scales. For climate change studies, the most familiar example is climate change forecasts at local scales, e.g., for a major city in a developing country. But the data gap is even more critical regarding impacts of climate change at a local scale, and it is still more problematic regarding local capacities to cope, adapt, and otherwise respond to risks or realities of impacts. Meanwhile, dealing with relatively localized scales by generalizing from a few detailed case studies is also problematic. This suggests that, for many purposes, balanced multi-scale or meta-scale synthesis is fundamentally undermined by data limitations at local scales.
– Creating formal quantitative structures that synthesize
  Incorporating meta-scale synthesis into integrated assessment modeling would ideally include a model component that provides an artificial-intelligence equivalent of human integrative judgment: not only combining numbers and applying mechanical algorithms but applying some form of synthesizing “reasoning.” This appears to be a laudable goal for the long term, but the fact remains that handling synthesis formally within the structure of an integrated assessment model requires quantitative structures appropriate to the questions being asked. A pertinent question at this stage is the degree to which this process can be generalized in integrated assessment models vs. being tailored for each question, represented in the overall modeling formulation as an exogenous input to be specified on a case-by-case basis. The current state of the art seems to require identifying a manageable number of key relationships for each case.
– Formalizing processes for combining quantitative and qualitative analysis
  One of the frontiers of integrated assessment, many practitioners believe, is transcending a boundary between quantitative analysis and non-quantitative components of an assessment process. Particular challenges range from incorporating expert judgment to incorporating narrative “stories,” scenarios, and analogs along with stakeholder knowledge bases [81]. One intriguing possibility is formal *qualitative* modeling, where broad insights do not depend on the precise shape of curves [43]. Another direction of interest is incorporating fuzzy logic in simulation modeling [55].

4. DIRECTIONS FOR IMPROVING OUR CAPABILITIES

If we want to improve our ability to meet these challenges, probably not by selecting a single operational approach for all purposes but by enhancing a variety of kinds of approaches as we learn further lessons from experience with integrated assessment modeling, what are the most important cross-cutting directions for research – and for research funding? In general, it appears that the easiest pieces of the puzzle to create are the computational ones, although such issues as the representation of uncertainty and nonlinearities continue to be challenges that transcend scale-related questions alone.

Rather than being limited by computational capabilities or the ability to model processes and relationships once we know them and have data about them, the state of the art is first of all profoundly data-limited [58, 82]. It is also still conceptually limited, not so much in representing more than one scale but in representing interscale processes and interactions.

Given these realities, I would suggest the following directions as sort of a skeleton for a multidisciplinary, multi-institutional, multinational research agenda to improve our capabilities for addressing scale and scaling issues in integrated assessment:

- ***Increase the availability of local or small-regional scale data, related to key issues and indicators.*** While this is obviously a resource-intensive process, it is an essential building block. One possible direction for exploration may be an expanded use of instrumentation for routine data-gathering; but it is important first to determine key indicators in order to assure that our modeling will be indicator-driven rather than merely data-driven.

- ***Improve longitudinal databases related to complex nature-society interactions and multiple stresses.*** A related need is to increase our knowledge base about interconnected phenomena and processes that cross-disciplinary boundaries, especially between nature and society, and to imbed our expanding understandings in comprehensive databases maintained over long periods of time.
- ***Identify key macroscale-microscale interaction issues and improve understanding of those key interactions.*** Along lines barely hinted at by Figure 4, we need to strengthen both theoretical and empirical understandings of the major components of cross-scale dynamics in global change processes, in order to determine how best to build this dimension into integrated assessment models.
- ***Explore tools for dynamic modeling of complex systems that are not now widely used in integrated assessment modeling.*** Most of our current modeling structures were built to understand process interactions at a very large scale. It is possible that structures intended to illuminate complex multi-scale system dynamics will need to use different tools, from system dynamics (or other approaches for deriving simultaneous solutions) to such alternatives as fuzzy logic, dynamic spatial simulation modeling, and applications of the science of complexity.
- ***Improve understandings of how to link analysis, assessment, deliberation, and stakeholder interaction.*** Finally, it seems clear that some aspects of the integrated assessment effort – especially related to upscaling from small-regional case study experiences, incorporating uncertainties in scenario construction, and involving stakeholders as experts in their own domains – will call for new paradigms for relating quantitative and non-quantitative contributions to our enterprise.

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