SCALING IN INTEGRATED ASSESSMENT

Editors

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Strategic Cyclical Scaling: Bridging Five Orders of Magnitude Scale Gaps in Climatic and Ecological Studies

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Scaling Paradigms in Modeling Coupled Systems

Integrated assessments of global change disturbances involve "end-to end" analyses of relationships and data from physical, biological and social sciences (e.g., see the reviews and references in Weyant *et al.* [1], Morgan and Dowlatabadi [2], Rotmans and van Asselt [3], Parson [4], Rothman and Robinson [5], Schneider [6]). Often, data or processes are collected or simulated across vastly different scales – for example, consumption at national scales and consumer preferences at family scales, or species competition at field plots the size of a tennis court and species range boundaries at the scale of a half continent, or thunderstorms at ten kilometers and the grid cells of a global climate model at hundreds of kilometers, or the response of an experimental plant in a meter-square chamber to increased concentrations of CO_2 but a prediction of ecosystem response to CO_2 at biome scales of a thousand kilometers. Not only must individual disciplines concerned with the impacts of global change disturbances – like altered atmospheric composition or land use and land cover changes – often deal with five orders of magnitude difference in spatial scales, but integrated studies must bridge scale gaps across disciplinary boundaries as well. For instance, how can a conservation biologist interested in the impacts of climate change on a mountaintop-restricted species scale down climate change projections from a climate model whose smallest resolved element is a grid square 250 kilometers on a side? Or, how can a climate modeler scale up knowledge of evapotranspiration through the sub-millimeter-sized stomata of forest leaves into the hydrological cycle of the climate model resolved at hundreds of kilometers? The latter problem is known as up-scaling (see e.g., Harvey [7]), and the former one,

downscaling (see e.g., Easterling *et al.* [8]). This cross-disciplinary aspect can be particularly daunting when different scales are inherent in different sub-disciplines with different traditions and methods – particularly likely in crossing natural and social scientific boundaries. Only a greater understanding of the methods and traditions of each of these sub-disciplines by practitioners in the others will likely help to facilitate that kind of epistemic boundary bridging across very different disciplines operating at very different scales.

Scaling in Natural Science Forecast Models. First, let us consider natural scientific scale bridging. The ideal for a credible forecasting model is to solve analytically a validated, process-based set of equations accounting for the interacting phenomena of interest. The classical reductionist philosophy in science is a belief that the laws of physics, for example, apply to phenomena at all scales. Thus, in principle, if such laws can be found (usually at small scales), then the solution of the equations that represent such laws will provide reliable forecasts at all scales. This assumes, of course, all significant phenomena are treated by the laws used in making the forecast.

Most climatic models, for example, are developed with the philosophy that solutions to the energy, momentum and mass conservation equations should, in principle, provide a credible forecasting tool. Of course, as all climate modelers have readily admitted for decades (e.g., SMIC [9], IPCC [10]), this "first principles," bottom-up approach suffers from a fundamental practical limitation: the coupled non-linear equations that describe the physics of the air, seas and ice are far too complex to be solved by any known (or foreseeable) analytic technique. Therefore, approximation techniques are applied in which the continuous differential equations (i.e. the laws upon which small scale physical theory comfortably rest) are replaced with discrete, numerical finite difference equations. The smallest resolved spatial element of such discrete models is known as a grid cell. Because the grid cells are larger than important small-scale phenomenon, such as the condensation of water vapor into clouds or the influence of a tall mountain on wind flow or the evapotranspiration from a patch of forest, "sub-grid scale" phenomena cannot be explicitly included in the model. In order to incorporate *implicitly* the effects of important sub-grid scale phenomenon into a model, top-down techniques are used, in which a mix of empiricism and fine-resolution, scale-up submodels are applied. This defines a parametric representation (or "parameterization") of the influence of sub-grid scale processes at large scales (e.g., grid size) as a function of variables that are resolved at the grid scale. A functional form is defined with free parameters that are calibrated to predict the effects of unresolved, sub-grid scale phenomena by associating them with grid-boxed averaged "large scale" variables. Determining whether it is even possible in principle to find valid parameterizations has occupied climate modelers for decades [9].

In order to estimate the ecological consequences at small scales of hypothesized climate change, a researcher must first translate the large-scale

climate-change forecast to a smaller-scale study region. This means, roughly speaking, translating climate information at a 500×500 km grid scale to, perhaps, a 50×50 M field plot – a ten-thousand-fold extrapolation! Therefore, how could climatologists map grid scale projections to landscapes and even smaller areas?

At the outset, one might ask why the atmospheric component of such detailed climate models, also known as general circulation models (GCMs), use such coarse horizontal resolution as hundreds of kilometers by hundreds of kilometers? This is easy to understand given the practical limitations of modern, and even foreseeable, computer hardware resources (e.g., Trenberth [11]).

A 50×50 km resolution is in the range known as "the mesoscale" in meteorology. If such a resolution were applied over the entire earth, then the amount of computation time needed on one of today's "super computers" to run a year's worth of weather would be on the order of many days. And, 50 km is still roughly two orders of magnitude greater than the size of a typical cloud and three orders of magnitude greater than the typical scale of an ecological study plot and even more orders of magnitude larger than a dust particle on which raindrops condense. Therefore, in the foreseeable future, climate-change information inevitably will not be produced directly from the grid cells of climate models at the same scale that most ecological information is gathered by the "scale-up" approach, nor will climate models be able to transcend the problem of unresolved sub-grid scale phenomena, such as cloudiness or evapotranspiration from plants.

Likewise, ecological modelers who attempt to be building models using "first principles" must also utilize top-down parameterizations. However, the usual scale mismatch between climate and ecological models is why some ecologists have sought to increase the number of large-scale ecological studies and some climatologists are trying to shrink the grid size of climate models. We argue that both are required, along with techniques to bridge the scale gaps, which unfortunately will exist for at least several more decades [12].

Finally, to mobilize action to correct potential risks to environment or society, it is often necessary to establish that a discernible trend has been detected in some variable of importance – the first arrival of a spring migrant or the latitudinal extent of the sea ice boundary for example – and that that trend can be attributed to some causal mechanism – a warming of the globe from anthropogenic greenhouse gases increases, for example. Pure association of trends in some variable of interest are not, by themselves, sufficient to attribute any detectable change above background noise levels to any particular cause – explanatory mechanistic models are needed and the predictions from such models should be consistent with the observed trend before a high confidence can be assessed that a particular impact can be pinned on any suspected causal agent. We will argue that conventional scaling paradigms – top-down associations among variables believed to be cause and effect;

bottom-up mechanistic models run to predict associations but for which there is no large-scale data time series to confirm – are not by themselves sufficient to provide high confidence in cause and effect relationships embedded in integrated assessments. Rather, we will argue that a cycling between top-down associations and bottom-up mechanistic models are needed. Moreover, we cannot assign high confidence to cause-and-effect claims until repeated cycles of testing in which mechanistic models predict and large scale data "verifies" and there is also a considerable degree of convergence in the cycling . We have called [13] this iterative cycling process "strategic cyclical scaling" (SCS), and elaborate on it a number of times in this article.

The SCS paradigm has two motivations: (1) better explanatory capabilities for multi-scale, multi-component interlinked environmental (e.g., climate-ecosystem interactions or behavior of adaptive agents in responding to the advent or prospect of climatic changes) and (2) more reliable impact assessments and problem-solving capabilities – predictive capacity – as has been requested by the policy community.

Bottom-up and Top-down Paradigms. The first standard paradigm is often known as "scale-up" or "bottom-up" or perhaps "micro" scale analysis. This is the idealized "first principles" approach attempted by most theoretical studies. That is, empirical observations made at small scales are used to determine possible mechanistic associations or "laws" that are then extrapolated to predict responses at a broad range of scales, particularly larger-scale responses. The second standard paradigm is often referred to as "scale-down" or "top-down" or "macro" scale analysis. For an ecological example, the correlation between biogeographic patterns (e.g., species range limits) and large-scale environmental variables (e.g., temperature, soil type) provides a means of predicting possible ecological responses to climate change for a broad range of scales, including smaller-scale responses. Each of these paradigms has been used extensively and we will cite below key examples of their applications to assessments of possible ecological consequences of anthropogenic disturbances, with a focus on global climatic change.

Deficiencies of the *singular* use of either top-down or bottom-up models, has led to well-known criticisms – also exemplified below. For scale-up, the primary problem is that some of the most conspicuous aspects of a system observable at the smaller scales may not easily reveal the dominant processes that generate large-scale patterns. The mechanisms creating larger-scale responses can be obscured in noisy and/or unrelated, local variations. This often leads to an inability to detect at small scales a coherent pattern of associations (i.e. mechanisms) among variables needed for impact assessments at large scales [14]. Scale-down approaches suffer because of the possibility that the discovered associations at large scales are statistical artifacts that do not, even implicitly, reflect the causal mechanisms that are needed to provide reliable forecasting [15].

Strategic Cyclical Scaling. This led us, therefore, to describe a third, less formalized paradigm, "Strategic Cyclical Scaling" (SCS). That is, macro and micro approaches are cyclically applied in a strategic design that addresses a practical problem: in our original context, the ecological consequences of global climatic change. The paradigm can be applied to many aspects of integrated assessments as well. Large-scale associations are used to focus small-scale investigations in order to develop valid causal mechanisms generating the large-scale relationships. Such mechanisms then become the systems-scale "laws" that allow more credible forecasts of the consequences of global change disturbances. "Although it is well understood that correlations are no substitute for mechanistic understanding of relationships," Levin [16] observed, "correlations can play an invaluable role in suggesting candidate mechanisms for (small-scale) investigation." SCS, however, is not only intended as a two-step process, but rather a continuous cycling between large- and small-scaled studies with each successive investigation building on previous insights from all scales. In other words, SCS involves the continuous refinement of predictive models by cycling between strategically designed large- and small-scaled studies, each building on previous work at large and small scales, repeatedly tested by data at both large and small scales to the extent they are available. This paradigm is designed to enhance the credibility of the overall assessment process, including policy analyses, which is why it is labeled "strategic." We believe that SCS is a more scientifically viable and cost-effective means of improving the credibility of integrated assessment, when compared to isolated pursuit of either the scale-up or scale-down method.

Knowing when the process has converged is a very difficult aspect of applying SCS, for that requires extensive testing against some applicable data that describes important aspects of the system being modeled. When the system is asked to project the future state of the socio-environment system, then there is no empirical data, only analogies from past data to use for testing. Therefore, assessing "convergence" will require judgments as well as empirical determinations.

Ecological Responses to Climate Changes as Scaling Examples

Bringing climatic forecasts down to ecological applications at local and regional scales is one way to bridge the scale gap across ecological and climatological studies. Ecologists, however, have also analyzed data and constructed models that apply over large scales, including the size of climatic model grids. A long tradition in ecology has associated the occurrence of vegetation types or the range limits of different species with physical factors such as temperature, soil moisture, land-sea boundaries, or elevation (e.g., Andrewartha and Birch [17]). Biogeography is the field that deals with such associations, and its results have been applied to estimate the large-scale ecological response to climate change.

Predicting Vegetation Responses to Climate Change. The Holdridge [18] life-zone classification assigns biomes (for example, tundra, grassland, desert, or tropical moist forest) according to two measurable variables, temperature and precipitation. Other more complicated large-scale formulas have been developed to predict vegetation patterns from a combination of large-scale predictors (for example, temperature, soil moisture, or solar radiation); vegetation modeled includes individual species [19], limited groups of vegetation types [20], or biomes [21, 22, 23]. These kinds of models predict vegetation patterns that represent the gross features of actual vegetation patterns, which is an incentive to use them to predict vegetation change with changing climate. As we explore in more detail later, such models have limitations. One criticism of such large-scale approaches is that, although the climate or other large-scale environmental factors are favorable to some biome that is actually present, these approaches also often predict vegetation to occur where it is absent – so-called commission errors. Other criticisms are aimed at the static nature of such models, which often predict vegetation changes to appear instantaneously at the moment the climate changes, neglecting transient dynamics that often cause a sequence or succession of vegetation types to emerge over decades to centuries following some disturbance (for example, fire), even in an unchanging climate. More recently, dynamic global vegetation models (DGVMs) have been developed to attempt to account for transitional dynamics of plant ecosystems (e.g., Foley *et al.* [24], Prentice *et al.* [25]).

Predicting Animal Responses to Climate Change. Birds. Scientists of the U.S. Geological Survey, in cooperation with Canadian scientists, conduct the annual North American Breeding Bird Survey, which provides distribution and abundance information for birds across the United States and Canada. From these data, collected by volunteers under strict guidance from the U.S. Geological Survey, shifts in bird ranges and abundances can be examined. Because these censuses were begun in the 1960's, these data can provide a wealth of baseline information. Price [26] has used these data to examine the birds that breed in the Great Plains. By using the present-day ranges and abundances for each of the species, Price derived large-scale, empirical-statistical models based on various climate variables (for example, maximum temperature in the hottest month and total precipitation in the wettest month) that provided estimates of the current bird ranges. Then, by using a general circulation model to forecast how doubling of CO_2 would affect the climate variables in the models, he applied the statistical models to predict the possible shape and location of the birds' ranges.

Significant changes were found for nearly all birds examined. The ranges of most species moved north, up mountain slopes, or both. The empirical models assume that these species are capable of moving into these more northerly areas, that is, if habitat is available and no major barriers exist. Such shifting of ranges could cause local extinctions in the more southern portions of the birds' ranges, and, if movement to the north is impossible, extinctions of entire

species could occur. We must bear in mind, however, that this empirical-statistical technique, which associates large-scale patterns of bird ranges with large-scale patterns of climate, does not explicitly represent the detailed physical and biological mechanisms that could lead to changes in birds' ranges. Therefore, the detailed maps should be viewed only as illustrative of the potential for very significant shifts with different possible doubled CO_2 climate change scenarios. More refined techniques that also attempt to include actual mechanisms for ecological changes are discussed later.

Herpetofauna. Reptiles and amphibians, which together are called herpeto-fauna (herps for short), are different from birds in many ways that are important to our discussion. First, because herps are ectotherms – meaning their body temperatures adjust to the ambient temperature and radiation of the environment – they must avoid environments where temperatures are too cold or too hot. Second, amphibians must live near water, not only because the reproductive part of their life cycle is dependent on water, but also because they must keep their skin moist because they breathe through their skin as well as their lungs. Third, herps are not able to disperse as easily as birds because they must crawl rather than fly, and the habitat through which they crawl must not be too dry or otherwise impassible (for example, high mountains or superhighways).

As the climate changes, the character of extreme weather events, such as cold snaps and droughts, will also change [27], necessitating relatively rapid habitat changes for most animals. Rapid movements by birds are possible since they can fly, but for herps such movements are much more difficult. For example, Burke (personal communication) noted that during the 1988 drought in Michigan, many more turtles than usual were found dead on the roads. He assumed they were trying to move from their usual water holes to others that had not yet dried up or that were cooler (for example, deeper). For such species, moving across roads usually means high mortality. In the long term, most birds can readily colonize new habitat as climatic regimes shift, but herp dispersal (colonization) rates are slow. Indeed, some reptile and amphibian species may still be expanding their ranges north even now, thousands of years after the last glacial retreat.

Burke and Root (personal communication) began analyzing North American herp ranges in an attempt to determine which, if any, are associated with climatic factors such as temperature, vegetation-greening duration, solar radiation, and so forth. Their preliminary evidence indicates that northern boundaries of some species ranges are associated with these factors, implying that climatic change could have a dramatic impact on the occurrence of herp species. It could also alter the population genetics within species since there can be genetic differences among populations with respect to climate tolerance. Many more extinctions are possible in herps than in birds because the forecasted human-induced climatic changes could occur rapidly when compared with the rate of natural climatic changes, and because the dispersal ability of most herps

is painfully slow, even without considering the additional difficulties associated with human land-use changes disturbing their migration paths.

The point of these examples in the context of our scaling issue discussion is that large-scale biogeographic associations may well be able to predict where herps would prefer to live if climate changes, but the detailed dynamics of their adjustments may lead to outcomes very different than if they somehow could just be transplanted to the new and more appropriate climate space. Transient dynamics and detailed small-scale studies are needed to be more confident that the large-scale associations will turn out to be predictive. Several reptile species could exhibit vulnerability to climatic change because of an unusual characteristic: their sex is determined by the temperature experienced as they develop inside the egg. Such temperature-dependent sex determination makes these animals uniquely sensitive to temperature change, meaning that climatic change could potentially cause dramatic range contractions due to biases in the sex ratios. For example, the European pond turtle, a species whose sex is determined by temperature, colonized England [28] and Denmark [29] during a warm period in the late Ice Age. With the return of colder temperatures, these populations rapidly disappeared. Holman (personal communication) suggested that a combination of shorter summers, which reduced available incubation time, and biased sex ratios, which were due to cooler summers, could easily have caused the swift retreat of this turtle to a more southern range.

Most North American turtles are subject to temperature-dependent sex determination [30, 31]; their populations can vary over the years from 100% males to 100% females [32, 33]. Janzen [33] found that sex ratios were closely linked to mean July temperature, and he demonstrated that under conditions predicted by climate change models, populations of turtles will regularly produce only females within 50 years.

In general, animals most likely to be affected earliest by climatic change are those in which populations are fairly small and limited to isolated habitat islands. As a result of human-generated landscape changes, many reptiles now fall into this category, as do many other animals. Indeed, temperature-dependent sex-determined species are especially likely to suffer from extreme sex ratio biases, and therefore their sensitivity to rapid climate change appears potentially more severe than most other animals. The latter assertion, of course, is a bottom-up projection based on mechanistic understanding of temperature-sex linkages, but this conjecture is yet to be tested at large scales where climatic changes are taking place – a step that would complete the first cycle of an SCS-oriented analysis.

Other Taxa. There are estimates that a number of small mammals living near isolated mountaintops (which are essentially habitat islands) in the Great Basin would become extinct given typical global change scenarios [34]. Recent studies of small mammals in Yellowstone National Park show that statistically significant changes in both abundances and physical sizes of

some species occurred with historical climate variations (which were much smaller than most projected climate changes for the next century), but there appear to have been no simultaneous genetic changes [35]. Therefore, it is likely that climate change in the twenty-first century could cause substantial alteration to biotic communities, even in protected habitats such as Yellowstone National Park. In addition, the biomass of macro-zooplankton in waters off southern California has decreased dramatically as surface waters warmed [36]. Similarly, a study suggests that statistically the range of the Edith's checkerspot butterfly in western North America has shifted northward and upward in association with long-term regional warming trends [37, 38].

Meta-analysis of some thousand species suggests that temperature trends of the latter few decades of the 20th century were sufficient to create a discernible impact in the traits of plants and animals widely scattered around the globe [39, 40]. These associations at large scales were established by predicting how each species should have reacted to warming based on micro studies of physiological ecology. Then, the meta-analysis showed that a vast disproportion of those species that exhibited changes changed in the direction expected from micro understanding of mechanisms. That disproportion at the large scale allowed the "discernible" statement of IPCC 2001 [39] to be scientifically credible. This has been, so far, only one cycle of SCS, but already that has allowed a confident conclusion in the assessment of climatic impacts on plants and animals.

Scaling Analysis of Ecological Responses

Top-Down Approaches. The biogeographic approach summarized above is an example of a top-down technique (for example, Holdridge's [18] life-zone classification), in which data on abundances or range limits of vegetation types or biomes are overlain on data of large-scale environmental factors such as temperature or precipitation. When associations among large-scale biological and climatic patterns are revealed, biogeographic rules expressing these correlations graphically or mathematically can be used to forecast changes in vegetation driven by given climate changes. Price's [26] maps of the changes in bird ranges are also an example of such a top-down approach. As noted earlier, though, such top-down approaches are not necessarily capturing the important mechanisms responsible for the association. Scientists therefore strive to look at smaller scales for processes that account for the causes of biogeographic associations, in the belief that the laws discovered at smaller scales will apply at large scales as well.

Bottom-Up Approaches. Small-scale ecological studies have been undertaken at the scale of a plant or even a single leaf [41] to understand how, for example, increased atmospheric CO_2 concentrations might directly enhance photosynthesis, net primary production, or water-use efficiency. Most of these

studies indicate increases in all these factors, increases that some researchers have extrapolated to predict global change impacts on ecosystems [42, 43].

To what extent can we reasonably project from experiments that use single leaves or single plants to more complex and larger environmental systems, such as an entire tundra [44] or forest ecosystem [45, 46, 47]? Forest ecosystem models driven only by global climate change scenarios in which CO_2 was doubled in a global circulation model typically project dramatic alteration to the current geographic patterns of global biomes [21, 23, 48]. But when such forest prediction models are modified to explicitly account for some of the possible physiological changes resulting from doubled CO_2, such as change in water-use efficiency, they use the empirical results from small-scale studies to extrapolate to whole forests. This bottom-up method dramatically reduces the percentage of land area predicted to experience biome change for any given climate change scenario [49]. Not all modelers have chosen to scale up from small scale experiments. Prentice et al. [21], for example, building on the work of McNaughton and Jarvis [50], excluded extrapolations of the effects of direct CO_2/water-use efficiency from their model.

At the scale of a forest covering a watershed, the relative humidity within the canopy, which significantly influences the evapotranspiration rate, is itself partly regulated by the forest. In other words, if an increase in water-use efficiency from direct CO_2 effects decreased the transpiration from each tree, the aggregate forest effect would be to lower relative humidity over the watershed scale. This, in turn, would increase transpiration, thereby offsetting some of the direct CO_2/water-use efficiency improvements observed experimentally at the scale of a single leaf or plant.

Moreover, leaves that have reduced evapotranspiration will be warmer, and if a forest full of them is heated by the sun it can increase the surface layer temperature, driving the planetary boundary layer higher, thereby increasing the volume into which boundary layer water vapor molecules can inhabit. This too lowers the relative humidity at leaf level, which in turn increases evapotranspiration rates – another negative feedback on water-use efficiency at the forest watershed scale that would not be perceived by experiments conducted in isolated chambers or even at the scale of a few tens of meters in actual forests. Regardless of the extent to which these forest-scale negative feedback effects will offset inferences made from bottom-up studies of isolated plants or small-scale field experiments, the following general conclusion emerges: the bottom-up methods may be appropriate for some processes at some scales in environmental science, but they cannot be considered credible without some sort of testing *at the scale of the system under study*. Schneider [51] has made the same point for climate models, as do several authors in the edited volume by Ehleringer and Field [52] for vegetation modeling. Harte et al. [53] used actual field experiments with heaters to simulate global warming as an experiment to demonstrate top-down/bottom-up connections.

Combined Top-Down and Bottom-Up Approaches. To help resolve the deficiencies of the top-down biome forest models mentioned previously, more process-based, bottom-up approaches such as forest-gap models have been developed [48, 54, 55]. These models include individual species and can calculate vegetation dynamics driven by time-evolving climatic change scenarios. Such models typically assume a random distribution of seed germination in which juvenile trees of various species appear. Whether these trees grow well or just barely survive depends on whether they are shaded by existing trees or grow in relatively well-lit gaps, what soil nutrients are available, and other environmental factors such as solar radiation, soil moisture, and temperature. Under ideal conditions, individual tree species are assigned a sigmoid (S-shaped) curve for growth in trunk diameter. So far, this approach may appear to be the desired process based, bottom-up technique, an impression reinforced by the spatial scale usually assumed, about 0.1 hectares. But the actual growth rate calculated in the model for each species has usually been determined by multiplying the ideal growth-rate curve by a series of growth-modifying functions that attempt to account for the limiting effects of nutrient availability, temperature stress, and so forth. These growth-modifying functions for temperature are usually determined empirically at a large scale by fitting an upside-down U-shaped curve, whose maximum is at the temperature midway between the average temperature of the species' northern range limit and the average temperature of its southern range limit. Growing degree-days (the sum of the number of degrees each day of the growing season above some threshold value of temperature) are used in this scenario.

In essence, this technique combines large-scale, top-down empirical pattern correlations into an otherwise mechanistic bottom-up modeling approach. Although this combined technique refines both approaches, it too has been criticized because such large-scale, top-down inclusions are not based on the physiology of individual species and lead to confusion about the fundamental and realized ranges [56]. (The fundamental range is the geographic space in which a given species could theoretically survive – for example, if its competitors were absent – and the realized range is where it actually exists.) The question then is: what limits the realized range, particularly at the southern boundary? Further, more refined models should include factors such as seed dispersal, so that plant recruitment is related to the preexisting population and is not simply the result of a random number generator in the computer code.

Studies using SCS Approaches. As noted, problems with the singular use of either top-down or bottom-up methods have led to well-known criticisms. A search of the literature [53, 57, 58] provides examples of a refined approach to analyzing across large and small scales – SCS. The need to combine scales in the context of a strategic assessment (i.e. global-problem solving) was succinctly stated by Vitousek [59: p173]: "... just as ecosystem ecology has advanced in large part through the use of ecosystem-level

measurements and experiments (i.e. scale-down), the science of global ecology is likely to develop most efficiently if it is driven by regional and global measurements designed to answer globally significant research questions."

Bird case study. The first example is gleaned from the work of one of us (TLR). One strategy for mitigating the warming of the globe by several ° C by the year 2050 is for policy makers to implement an abatement policy. Such a policy, of course, could be economically damaging to some sectors. Before policy makers (or the general public, for that matter) would be willing to endorse a strong mitigation policy, they would like a sense of what the possible consequences of such warming might be. By analogy, a patient will be much more willing to take powerful drugs or make a dramatic change in lifestyle or eating habits if the physician explains a severe heart attack is probable without such changes. Humans resist change, particularly major change, unless the actual (or perceived) cost of not changing is high enough (e.g., death from a heart attack). Hence, knowing what the possible ecological "cost" of various warming scenarios is would be very helpful for policy makers [60, 61, 62, 63]. With that strategic end and systems understanding both in mind, Root [64] examined the biogeographic patterns of all wintering North American birds.

Large-scale abundance data requires a veritable small army of census takers and the National Audubon Society has such "armies" amassed to facilitate the collection of the Christmas Bird Count data. Using these data, Root [65] determined that a large proportion of species have their average distribution and abundance patterns associated with various environmental factors (e.g., northern range limits and average minimum January temperature). The scaling question is: What mechanisms at small scales (e.g., competition, thermal stress, etc.) may have given rise to the large-scale associations? Root [66] first tested the hypothesis that local physiological constraints may be causing the particular large-scale temperature/range boundary associations. She used published small-scale studies on the wintering physiology of key species and determined that roughly half of the song birds wintering in North America extend their ranges no further than into regions where raising their metabolic rates to less than roughly 2.5 times their basal metabolic rate will allow them to maintain their body temperature throughout the winter nights. The actual physiological mechanisms generating this "2.5 rule" [67] required further investigation at small scales.

Field and laboratory studies examining various physiological parameters (e.g., stored fat, fat-metabolizing enzymes, various hormones) are being examined on a subset of those species that were found in the large-scale study to have northern range boundaries apparently constrained by physiological mechanisms in response to nighttime minimum temperature. Several intensive small-scale studies were executed along a longitudinal transect running from Michigan to Alabama in order to examine patterns on a geographic scale. Root [58] found that the amount of stored fat (depot fat) may be limiting, in that the estimated amount of available fat at dawn under extreme conditions

was much lower for those individuals near their northern range boundary than for those in the middle of their range. To determine the relative importance between colder temperatures or longer nights and thereby fewer hours of daylight available for foraging, Root [40] has embarked on a larger regional study. In addition to the one longitudinal transect, she incorporated another transect, which runs from Iowa to Louisiana. This larger-scale design was selected based on previous small-scale studies because it allows a decoupling of the effects of day length and temperature. The decoupling, in turn, is important to the strategic problem of determining whether or not scenarios of global warming might have a large effect (e.g., if temperature proves to be more important than day length). Preliminary results are suggesting that changing temperatures, more than day length are explanatory [40]. These, in turn, suggest global temperature changes would likely cause rapid range and abundance shifts by at least some bird species.

Rapid changes in the large-scale patterns (e.g., ranges) of birds are possible. Indeed, Root's [58] finding that suggests significant annual shifts in species ranges, led to yet another large-scale, top-down study, but this time looking for associations in the year-to-year variations (rather than average range limits or abundances as before) between large-scale patterns of birds and climate variables. The first step has been to quantify the year-to-year variations of selected species. The next step is to perform time series analyses of 30 years of wintering bird abundance data with key climate variables (e.g., number of days below $X°$ C). Preliminary analysis for only one species at two sites shows that in warmer years more individuals winter farther north than in colder years [68]. While no claim is being offered at this point in the research for the generality of those preliminary results that suggest strong and quantitative links between year-to-year changes in bird abundances and climate variability, this example does permit a clear demonstration of the SCS paradigm. However, extending this type of analysis to other taxa (reptiles in this case) may prove to be a fruitful approach. Additionally, combining such information from various taxa will allow a much better understanding of possible ecological consequences of climatic change (e.g., see IPCC [39, 60] for an update and references to the recent literature).

COHMAP case study.

Our first example of the use of the strategic cyclical scaling type of approach dealt primarily with a single investigator. The second example is that of a team effort, which has the advantage of entraining dozens of diverse people and facilities from many institutions, but has the disadvantage of requiring coordination of all those researchers and facilities. The COHMAP study has been noteworthy because of its important findings with regard to "no-analog" vegetation communities during the transition from ice age to interglacial about 12,000 years ago (e.g., Overpeck et al. [69]). But this large team effort went well beyond the gathering of local field data at enough sites to

document the paleohistories of particular lakes or bogs – they compiled the local studies into large scale maps. The COHMAP researchers strategically designed their field and lab work to compliment large-scale climatic modeling studies using GCMs. Accepting the premise that climate changes from 20,000 years ago to the present were forced by changes in the Earth's orbital geometry, greenhouse gas concentrations and sea surface temperatures, and knowing that such changes can be applied as boundary forcing conditions for GCMs, the COHMAP team used a GCM to produce 3,000-year-apart maps of changing climate from these varying boundary conditions. They used regressions to associate pollen percentages from field data with climatic variables (January and July temperatures and annual precipitation). They drew large-scale maps of fossil pollen abundance every three thousand years from 18,000 years ago to the present. The top-down formulas that relate climate change to pollen abundances were then used to predict how climate had changed. These paleoclimate maps were then compared to GCM maps to (a) help explain the causes of climatic and ecological changes, and (b) help validate the regional forecast skill of GCMs driven by specified large-scale external forcings. The latter is a practical problem of major policy significance, because the credibility of GCMs regional climatic anomaly forecasts are controversial in the context of global warming and its ecological consequences. Thus, this validation exercise is a clear strategically-focused attempt at model validation at the scale of the model's resolution. The investigation did not end there, but cycled between previous large- and small-scale studies, which led to further predictions using GCMs. To enhance this validation exercise, Kutzbach and Street-Perrott [70] developed a regional-scale hydrological model to predict paleo-lake levels in Africa and used these coupled models to compare lake levels over the past 18,000 years computed from GCM-climates driving the hydrology model with paleo-lake shore changes inferred from fossil field data at micro scales. The comparisons between coupled GCM-hydrological models and paleo-lake data were broadly consistent, and when combined with the vegetation change map comparisons between GCM-produced pollen abundances and field data on pollen abundances, these comparisons have provided a major boost to the credibility of GCM regional projections of forced climate changes.

Webb et al. [71] used the multi-institutional, multi-scale, interdisciplinary COHMAP effort, with its strategic design and the cycling between scale-up and scale-down approaches and drawing on many disciplines. Not only do the participants deserve credit for experimenting with such a progressive, strategic research design that addresses earth systems problems across many scales and cycles between scale-up and scale-down methods, but credits should also go to the many institutions that cooperated and foundations that funded this non-traditional, SCS-like effort. We believe that as long as most discipline-oriented research institutions and funding agencies remain organized in disciplinary sub-units, that many more multi-institutional projects like COHMAP that implicitly or explicitly use the SCS-like paradigm as their

interdisciplinary research design will be needed to address the ecological implications of climate change. We also believe that fundamental, structural institutional changes to foster interdisciplinary, multi-institutional research is long overdue.

The Webb *et al.* [71] results showed that during the most rapid transition from ice age to interglacial conditions about 12,000 years ago, that large tracts of "no-analog" habitats existed, in which communities of plants had no resemblance to communities found today. This suggests that future plant communities driven by anthropogenic climate changes would also contain many no-analog components.

Strategic cyclical scaling, however, is not only intended as a two-step process, but also as a continuous cycling process between large- and small-scale studies, with each successive investigation building on previous insights from all scales and with testing at all scales as an integral step in the hope of achieving some measure of convergence as further cycles are applied. This approach is designed to enhance the credibility – and thus policy utility – of the overall assessment process (see also Vitousek [59], Harte and Shaw [72]), which is why strategic is the first word in strategic cyclical scaling.

Integrated Assessment via Coupled Socio-Natural Systems Models

Abrupt behavior as an emergent property of a coupled socio-natural system model for oceanic model coupled to an optimizing energy-economy model. Paleoclimate reconstruction and model simulations suggest there are multiple equilibria for thermohaline circulation (THC) in the North Atlantic (also known as the "conveyor belt"), including complete collapse of this circulation responsible for the equable climates of Europe. Switching between the equilibria can occur as a result of temperature or freshwater forcing. Thus, the pattern of THC that exists today could be modified by an infusion of fresh water at higher latitudes or through high latitude warming. These changes may occur if climate change increases precipitation, causes glaciers to melt, or warms high latitudes more than low latitudes, as is often projected [10, 39].

Further research has incorporated this behavior into coupled climate-economic modeling, characterizing additional emergent properties of the coupled climate-economic system [73]. Again, this coupled multi-system behavior is not revealed by single-discipline sub-models alone – e.g., choices of model parameter values such as the discount rate determine whether emissions mitigation decisions made in the near-term will prevent a future THC collapse or not – clearly a property not obtainable by an economic model *per se.*

If warming reduces the ability of surface water to sink in high latitudes, this interferes with the inflow of warm water from the south. Such a slow-down will cause local cooling – re-energizing the local sinking, serving as a stabilizing negative feedback on the slowdown. On the other hand, the initial

slowdown of the strength of the Gulf Stream reduces the flow of salty subtropical water to the higher latitudes of the North Atlantic. This would act as a destabilizing positive feedback on the process by further decreasing the salinity of the North Atlantic surface water and reducing its density and thus further inhibiting local sinking. The rate at which the warming or freshwater forcing is applied to the coupled system could determine which of these opposing feedbacks dominates, and subsequently whether a THC collapse occurs (e.g., Schneider and Thompson [74]).

Recent research efforts have connected this abrupt non-linearity to integrated assessment of climate change policy. William Nordhaus' DICE model [75] is a simple optimal growth model. Given a set of explicit value judgments and assumptions, the model generates an "optimal" future forecast for a number of economic and environmental variables. It does this by maximizing discounted utility (satisfaction from consumption) by balancing the costs to the economy of greenhouse gas (GHG) emissions abatement (a loss in a portion of GDP caused by higher carbon energy prices) against the costs of the buildup of atmospheric GHG concentrations. This buildup affects the climate, which in turn causes "climate damage," a reduction in GDP determined by the rise in globally averaged surface temperature due to GHG emissions. In some sectors and regions such climate damages could be negative – i.e. benefits – but DICE aggregates across all sectors and regions (see, for example, the discussions in Chapters 1 and 19 of IPCC [39]) and thus assumes that this aggregate measure of damage is always a positive cost.

Mastrandrea and Schneider [73] have developed a modified version of Nordhaus' DICE model called E-DICE, containing an enhanced damage function that reflects the higher likely damages that would result when abrupt climate changes occur. If climate changes are smooth and thus relatively predictable, then the foresight afforded increases the capacity of society to adapt, hence damages will be lower than for very rapid or less anticipated changes such as abrupt unanticipated events – "surprises" such as a THC collapse. It is likely that, even in a distant future society, the advent of abrupt climatic changes would reduce adaptability and thus increase damages relative to smoothly varying, more foreseeable changes.

Since the processes that the models ignore by their high degree of aggregation require heroic parameterizations, the quantitative results are only used as a tool for insights into potential qualitative behaviors. Because of the abrupt non-linear behavior of the SCD model, the E-DICE model produces a result that is also qualitatively different from DICE with its lack of internal abrupt non-linear dynamics. A THC collapse is obtained for rapid and large CO_2 increases in the SCD model. An "optimal" solution of conventional DICE can produce an emissions profile that triggers such a collapse in the SCD model. However, this abrupt non-linear event can be prevented when the damage function in DICE is modified to account for enhanced damages

created by this THC collapse and THC behavior is incorporated into the coupled climate-economy model.

The coupled system contains feedback mechanisms that allow the profile of carbon taxes to increase sufficiently in response to the enhanced damages so as to lower emissions sufficiently to prevent the THC collapse in an optimization run of E-DICE. The enhanced carbon tax actually "works" to lower emissions and thus avoid future damages. Keller *et al.* [76] support these results, finding that significantly reducing carbon dioxide emissions to prevent or delay potential damages from an uncertain and irreversible future climate change such as THC collapse may be cost-effective. But the amount of near-term mitigation the DICE model "recommends" to reduce future damages is critically dependent on the discount rate (e.g., see Fig. 1 from Mastrandrea and Schneider [73]). Figure 9.1 is a "cliff diagram" showing the equilibrium THC overturning for different combinations of climate sensitivity and pure rate of time preference (PRTP) values. As the PRTP decreases, "normal" circulation is preserved for disproportionately higher climate sensitivities since the lower PRTP leads to larger emissions reductions in E-DICE and thus it takes a higher climate sensitivity to reach the "cliff." Thus, for low discount rates (PRTP of less than 1.8% in one formulation – see Fig. 4 in Mastrandrea and Schneider [73]) the present value of future damages creates a sufficient carbon tax to keep emissions below the trigger level for the abrupt non-linear collapse of the THC a century later. But a higher discount rate sufficiently reduces the present value of even catastrophic long-term damages such that an abrupt non-linear THC collapse becomes an emergent property of the coupled socio-natural system – with the discount rate of the 21st century becoming the parameter that most influences the 22nd century behavior of the modeled climate.

Although these highly aggregated models are not intended to provide high confidence quantitative projections of coupled socio-natural system behaviors, we believe that the bulk of integrated assessment models used to date for climate policy analysis – and which do not include any such abrupt non-linear processes – will not be able to alert the policymaking community to the importance of abrupt non-linear behaviors. At the very least, the ranges of estimates of future climate damages should be expanded beyond that suggested in conventional analytic tools to account for such non-linear behaviors (e.g., Moss and Schneider [77]).

Role of SCS in the coupled E-DICE/SCD integrated assessment model. The Mastrandrea and Schneider [73] example just presented has scale bridging – explicitly and implicitly – embedded in virtually every aspect. First of all, the DICE model uses a hypothetical economic "agent" to maximize the utility given a number of assumed conditions. This is a major scale assumption – that individual behavior is only to maximize utility defined as Nordhaus [75] has (the logarithm of consumption). Indeed, there is no SCS in this formulation, just an assumption that individual utility-consumption maximizing
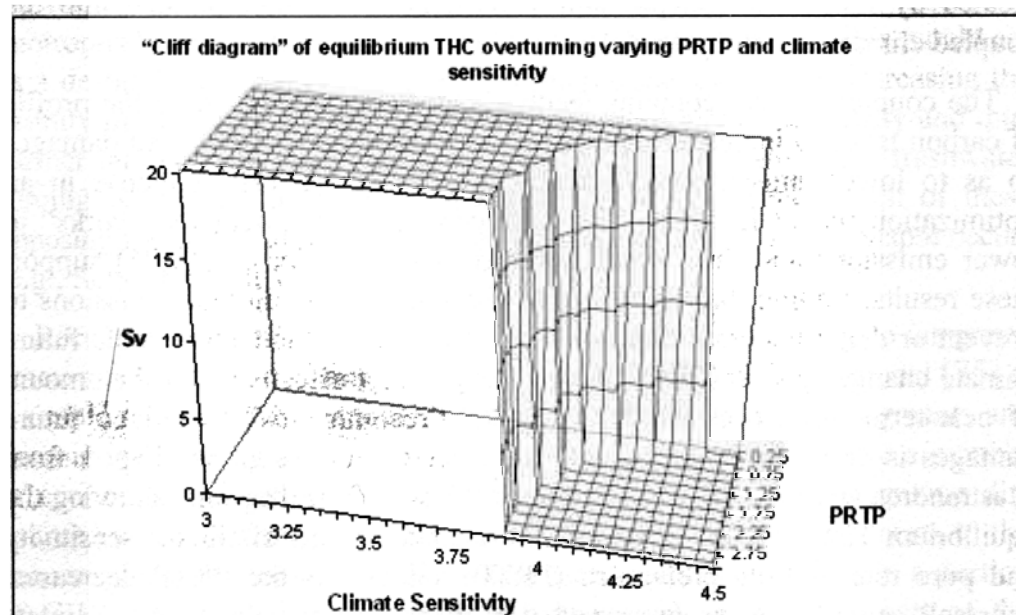
Figure 9.1: "Cliff diagram" of equilibrium THC overturning varying PRTP and climate sensitivity. Two states of the system – "normal" (20Sv) and "collapsed" (0Sv) THC – are seen here. The numbers are only for illustration as a several parameters relevant to the conditions in which the THC collapse osccurs are not varied across their full range in this calculation, which is primarily shown to illustrate the emergent property of high sensitivity to discounting in a coupled socio-natural model (Source: Mastrandrea and Schneider [73]).

behaviors of some can be scaled up to a global agent that utility maximizes. An SCS approach could have been (based on micro studies of individual behaviors) to modify the agency formulation such that as people got richer they changed their fondness for material consumption and their preferences switched to other attributes – equity or nature protection, perhaps. Clearly, such an integrated assessment model as DICE has not yet begun to exploit the possibilities for alternative formulations via an SCS approach.

Second, the DICE integrated assessment model assumes that people – that is, their agent – discount with a fixed social rate of time preference. Some empirical studies at micro levels suggest that people do not discount via standard exponential formulae, but rather use hyperbolic discounting (e.g., Heal [78]) – a very high initial discount rate, but a diminishing rate for far distant events. This formulation would substantially increase the present value of catastrophic events like a THC collapse in the 22nd century, as is shown in one of the Mastrandrea and Schneider [73] cases. That, in turn, leads to much higher "optimal" carbon control rates and thus reduced likelihood of collapsed THC in the distant future. Again, this scale-up assumption for discounting in DICE is not treated via SCS in the current formulation, but could be if the modeling design were to explicitly account for how agents might behave given the broad set of preferences in different societies (e.g., see Van Asselt and Rotmans [79]) or for alternative future states of the simulation

Additionally, the ocean model is a reduced form (a scale-up) representation of a micro law – salty and colder water is denser than warmer and fresher water. But SCS is not entirely absent in this example, since the parameters that are used in the THC overturning model derived from micro laws like the oceanic density formula were obtained by adjusting the performance of the simple model to reproduce the behaviors of much more comprehensive GCMs. These GCMs do cycle between large and small scales in the determination of their parametric representations of sub-grid scale phenomena, and thus their use to "tune" the SCD model via adjusting its free parameters to obtain behaviors similar to the more complex models does involve cycling across scales.

Clearly, more refined formulations of coupled socio-natural macro models to include better micro representation of agency, discounting and definitions of utility that extend beyond material consumption are badly needed in the next generation of such integrated assessment models that attempt to include abrupt system changes (see e.g., Table 2 in Schneider [6]). Social dimensions, such as the scaling of understanding from the levels of individual cognition to social class to institutional organizations, have only begun to be considered in integrated assessment modeling, Further refinements in the natural system sub-models could include (a), better treatment of moisture transport into the North Atlantic region based on smaller scale analyses or (b), micro damage functions built from the bottom up – for example explicit representation of fisheries, forests or agriculture in a Europe cooled by THC collapse – rather than a simple top-down aggregated damage function in which GDP loss is proportional to the square of the warming (the DICE formulation). Further disaggregation into regional resolution for both socio and natural sub-models would add another layer of cross-scale integration, and SCS would again be a technique to help design alternative formulations – as has already been attempted in regional integrated assessment models like IMAGE (e.g., Alcamo [80]) to study climate change – but in the context of smooth, rather than abrupt, variation modes.

Conclusions

We have suggested that progress in bridging orders of magnitude differences in scale may be aided by use of the cycling across scales in which micro information of processes and mechanisms is used to make predictions at larger scales, and then data at larger scales is used to test to predictions, after which future micro refinements are performed in light of the testing at macro levels. We show that this process is easiest to apply when the distances across the disciplines that are coupled is not too great – within ecology or ecology coupled to climate – our prime examples developed above. We also suggest – and give an example – that this becomes more difficult in practice when natural and social scientific sub-models are coupled – at least until an interdisciplinary epistemic community emerges in which each sub-discipline learns

enough about the methods and traditions of the other sub-disciplines to communicate meaningfully.

We also note that although convergence of cycling across scales may occur for some problems, where fundamental data is lacking to test – at micro or macro scales – or where functional relationships among variables are still highly uncertain, convergence may not be easily obtained. It is difficult to fashion a set of rules for applying SCS, but clearly the keys are to have (a) a reasonable idea of processes/mechanisms at smaller scales (b) some relevant data sets at large scales to test the predictions of models built on the micro level understanding, and (c) the development and fostering of interdisciplinary teams, and eventually, interdisciplinary communities, capable of unbiased peer reviewing of cross-scale, cross-disciplinary analyses in which the bulk of the originality is in the integrative aspects, rather than advances in the sub-disciplines that are coupled. Several of the contributions in this volume are excellent examples of the progress that is being made in fostering the development of such an interdisciplinary community, progress that is essential to the growth and credibility of the integrated assessment of climate change.

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