Scaling From Site-Specific Observations to Global Model Grids

A Report of the Aspen Global Change Institute
Elements of Change Series

Susan Joy Hassol
John Katzenberger

Editors

Aspen Global Change Institute

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CO-CHAIRS:
Danny Harvey

WRITER-EDITORS:
Susan Joy Hassol

ELEMENTS OF CHANGE SERIES EDITOR:
John Katzenberger

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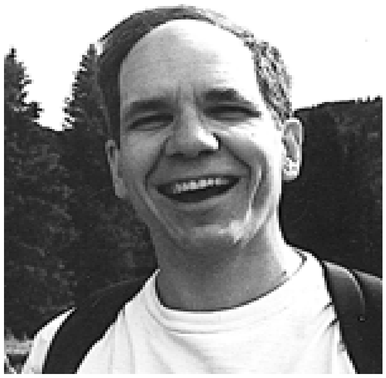
ASPEN GLOBAL CHANGE INSTITUTE
100 EAST FRANCIS STREET • ASPEN COLORADO 81611
970 925 7376 • agcimail@agci.org • www.agci.org

Table of Contents

Acronyms

AGCI Aspen Global Change Institute
ARM Atmospheric Radiation Measurement
AVHRR Advanced Very High Resolution Radiometer
BATS Biosphere-Atmosphere Transfer Scheme
BESIS Bering Sea Impacts Study
CCM Community Climate Model
CENR Committee on Environment and Natural Resources
DOE Department of Energy
DOI Department of Interior
EPA Environmental Protection Agency
ENSO El Niño/Southern Oscillation
ET Evapotranspiration
FAST Fourier Amplitude Sensitivity Test
FEMA Federal Emergency Management Administration
FERC Federal Energy Regulatory Commission
FFES Fossil Free Energy Scenario
FIFE First ISLCP Field Experiment
GCM General Circulation Model
GDP Gross Domestic Product
GHG Greenhouse Gas
GIS Geographic Information System
GCLP Global Change in Local Places
GLOBE Global Learning and Observations to Benefit the Environment
IBIS Integrated Biosphere Simulator
IPCC Intergovernmental Panel on Climate Change
ISLCP International Satellite Land-surface Climatology Project
LAI Leaf Area Index
LAID Land-Atmosphere Interactions Dynamics
LES Large-Eddy Simulations
LESS Low-Emissions Supply System
LIDAR Light Detection and Ranging Instrument
LSP Land Surface Processes
LSX Land Surface Exchange
LWC Liquid Water Content
NACO National Assessment Coordination Office
NAFTA North American Free Trade Agreement
NALT National Assessment Leadership Team
NASA National Aeronautics and Space Administration
NAST National Assessment Synthesis Team
NAWG National Assessment Working Group
NCAR National Center for Atmospheric Research
NGO Non-governmental Organization
NOAA National Oceanic and Atmospheric Administration
NPP Net Primary Productivity
NSF National Science Foundation
NSTC National Science and Technology Council
NWP Numerical Weather Prediction
OSTP Office of Science and Technology Policy
PAR Photosynthetically Active Radiation
PFT Plant Functional Type
PILPS Project for Intercomparison of Land Surface Parameterization Schemes
PLAID Patchy Land-Atmosphere Interactions Dynamics
RAMS Regional Atmospheric Modeling System
SCM Single Column Model
SGCR Subcommittee on Global Change Research
SiB Simple Biosphere Model
SVATS Soil Vegetation Atmosphere Transfer Schemes
TOGA-COARE Tropical Ocean Global Atmosphere Combined Ocean Atmosphere Response Experiment
TNC Total Non-Structural Carbon
TREGRO Tree Growth Model
USDA U. S. Department of Agriculture
USGCRP United States Global Change Research Program
VEMAP Vegetation/Ecosystem Modeling and Analysis Project
WG Working Group (of IPCC)
WGNE Working Group on Numerical Experimentation



Session Synthesis Essay: Upscaling in Global Change Research

Danny Harvey, Session Chair

University of Toronto
Toronto, Canada

"Upscaling" was taken to mean the process of extrapolating from the site-specific scale to the grid cell size found in global models used to study global environmental change

This session of the Aspen Global Change Institute (AGCI) examined the problem of upscaling in global change research. The term "global environmental change" was meant to mean changes that are global by virtue of the fact that they involve systemic changes in the properties of the atmosphere or ocean, or changes that, although local or regional in scale, are so widespread in their occurrence that they can be regarded as global-scale problems. The term "upscaling" was taken to mean the process of extrapolating from the site-specific scale at which observations are usually made or at which theoretical relationships apply, to the grid cell size found in global models used to study global environmental change. Upscaling is concerned with the development of relationships that are applicable at the grid-cell scale of models, so that they can be implemented in such models as part of the process of developing projections for the future. It is distinct from the problem of downscaling, which also arises in global change research. The latter is concerned with taking the output of global change models and deducing the changes that would occur at finer scales than resolved by the model. The two problems are not entirely independent, however, in that common processes underlie both scaling problems. Upscaling is a process-oriented problem, but there are other issues involving scale that do not constitute upscaling (or downscaling). For example, predictability generally depends on scale, but the determination and description of how predictability varies with scale is not a scaling problem.

This essay summarizes the introductory presentation made at the workshop by the author and chair, in which the major upscaling issues and problems in a wide variety of disciplines were identified, followed by a classification of upscaling problems in terms of the underlying causes and a comparison of the techniques that have been used to address the upscaling issue in different disciplines. This essay is a condensed version of a more extensive treatment of upscaling found in Harvey (1998), which is part of a special issue of Climatic Change based on the AGCI workshop.

Key Questions

A number of important questions of relevance to upscaling were identified at the beginning of the meeting, and answers or partial answers to some of the questions emerged and are presented in this overview. The key questions raised were:

(1) When is upscaling possible?

(2) For cases where upscaling is possible, how should it be done?

(3) For cases in which a given phenomenon has been (largely) independently examined at two or more scales by workers within the same discipline, how can results be properly intercompared?

(4) What are the implications of scaling issues for such things as predictability, parameterization, and the response and vulnerability of ecosystems and human societies to global and local environmental change?

(5) What are the relationships between upscaling and downscaling problems?

(6) How does the relationship between changes in variability and changes in the mean change as the scale changes?

When is upscaling possible? How should it be done? What are its implications for predictability?

(7) How does variability change with scale?

(8) How does predictability change with scale?

(9) How do errors propagate with scale?

Surface hydrology

Scaling issues arise in surface hydrology for three fundamentally different reasons: due to the existence of strong spatial heterogeneity in surface processes and rainfall intensity combined with strongly nonlinear processes; because different processes require a different minimum scale in order to occur in the first place; and because different processes can dominate the overall system at different scales.

Spatial heterogeneity combined with nonlinearity is particularly important for interception of rainfall by vegetation, and for infiltration and runoff. Subgrid-scale variations can occur in rainfall intensity, antecedent soil moisture, soil hydraulic properties, or in vegetative properties. The usual practice in atmospheric General Circulation Models (GCMs) is to employ a lumped model , in which a point process model is applied to the entire grid cell domain, with no change in structure, using the grid-cell average precipitation and surface properties. An alternative is to use a distributed model, in which the process model is applied at (distributed over) a large number of sites or patches within the grid cell, and the results are summed. This requires assuming some distribution function for the rainfall, and requires knowledge of the distribution of soil and vegetation properties within the grid cell. Distributed models can be applied in a deterministic manner using the specific spatial distribution of input parameters or in a stochastic manner, in which only the functions describing the probability distribution for each input parameter need to be known. An alternative to distributed models is to use a lumped model with effective parameters whose values are not simple arithmetic averages of the sub-grid parameter values. A problem with this approach is that there are parameters (such as soil hydraulic conductivity), where no single effective value works for all soil moisture conditions (Blöschl and Sivapalan, 1995).

The second scaling problem in surface hydrology is that different processes require a different minimum scale in order to occur. Surface runoff generation in nature involves two distinct processes: the occurrence of overland flow (“Hortonian” runoff) when precipitation rate exceeds infiltration rate, and precipitation on saturated regions. Hortonian overland flow is a point process, whereas saturated overland flow requires a minimum upslope catchment area before it

can begin. Entekhabi and Eagleson (1989) developed a parameterization of runoff generation that incorporates these two separate mechanisms and their changing relative importance, during the coarse of a rainfall event, at the model grid scale.

The third scaling problem is that the dominant process can change as the scale under consideration changes. Thus, matrix flow - the flow of water through the pores within the bulk of a soil sample - gives way to preferential flow in certain concentrated regions when viewed at a larger scale (Blöschl and Sivapalan, 1995).

Surface-air fluxes of heat, trace gases, and momentum

In some cases, the use of grid-average parameter values is a valid approach, while in other cases a distributed model is required.

In global-scale climate models, the vertical fluxes of heat, water vapor, and momentum between the land surface and atmosphere are usually computed using relationships that were developed at the scale of a few square meters to tens of square meters. These relationships are applied to the entire grid cell, without modification, using the grid-average parameter values as inputs. Since the heat fluxes depend non-linearly on surface moisture and resistance, there is the potential for large errors in the grid-average fluxes. A number of researchers have compared the grid-scale fluxes computed by this lumped approach with fluxes computed using a statistically distributed model. In some cases, the use of grid-average parameter values is a valid approach (e. g., Wood and Lakshmi, 1993; Sellers et al., 1995), while in other cases a distributed model is required (e. g., Bonan et al., 1993; Li and Avissar, 1994; Arola and Lettenmaier, 1996).

Bonan et al. (1993) note that the true statistical distribution of key input parameters (leaf area index, stomatal resistance, soil wetness) is unknown, so the importance of subgrid-scale variability for global climate simulations cannot yet be assessed. As in the treatment of surface hydrology, an alternative to the use of a statistically distributed model is to apply the point process model to the entire grid cell, but using effective parameter values (the lumped approach), as in Chenbouni et al. (1995). A second alternative is to develop a new model structure that is applicable at the larger scale, an approach adopted by Wetzel and Chang (1987).

Another key input, that is important for the vertical fluxes of heat, moisture, and momentum, is the roughness of the surface. The effective roughness height needed in order to compute the vertical flux of momentum between the surface and atmosphere at a scale of 10 km can be an order of magnitude larger than the local value. This is due to the existence of drag on dispersed obstacles covering a small fraction of the grid cell. However, the effective roughness height for heat (and water vapor) tends to decrease with increasing scale since heat transfer is not concentrated on obstacles. This essence of the scaling problem in this case is that the surface looks different at different scales.

Free-air vertical heat fluxes and interactions with clouds

The vertical fluxes of heat and water immediately adjacent to the land surface depend on turbulence, and thus involve random motions that have no preferred horizontal spatial structure. As one moves a few tens to hundreds of meters above the surface, however, organized air motions on a scale of one to several tens of kilometers can arise. These are referred to as mesoscale motions, and are intermediate in scale between turbulence and those motions that can be resolved by GCMs. These motions are dependent on surface heterogeneity, as variations in surface temperature (related to differences in soil moisture and albedo) can produce regions of concentrated uplift (convection), separated by regions of subsidence (sinking motion). Given that mesoscale motions depend on the typical spatial extent of surface heterogeneities,

as well as on the larger scale atmospheric conditions (such as stability and wind velocity), it might be possible to parameterize the effects of mesoscale motions. Lynn et al. (1995) and Zeng and Pielke (1995) present initial attempts at developing parameterizations of the effects of mesoscale motions on the vertical sensible and latent heat fluxes.

Interactions with clouds, which were not considered by Lynn et al. (1995) or Zeng and Pielke (1995), complicate the picture further. Wetzel and Boone (1995) proposed a parameterization for the effect of surface heterogeneity on non-precipitating cumulus clouds, using either deterministically or stochastically distributed surface patches coupled to a single atmospheric layer that covers all the patches. However, their scheme does not include the effects of mesoscale motions. Thus, although one may be able to successfully aggregate surface heterogeneity in computing grid-cell mean sensible and latent heat fluxes, a much more difficult and as yet unresolved scaling problem remains when it comes to interaction between the surface and clouds. It might be that the effect of mesoscale motions is simply to change the distribution of precipitation but not the total precipitation within a GCM grid cell, but the conditions under which this is the case remain to be defined.

A second scaling problem for clouds arises due to the existence of spatial variability within atmospheric grid boxes, involving humidity. At a given point, condensation requires a relative humidity of 100 percent. Upscaling to the grid-cell is accommodated in atmospheric models by setting the threshold for cloud formation at something less than 100 percent relative humidity, to account for the fact that parts of the cell can be saturated even when the mean relative humidity is less then 100 percent.

A third scaling problem related to clouds involves accounting for the effect of ensembles or collections of cumulus clouds within a single grid cell. A cumulus cloud modifies the air around it through detrainment of water vapor and liquid water at the top of the cloud, and through the induced subsidence of air adjacent to the cloud.

The mass flux and vertical extent of each cloud, however, depend on the large-scale atmospheric conditions. At any given time there will be a collection of cumulus clouds of varying thickness and hence varying heights of detrainment. The presence of each cumulus cloud in an ensemble influences the occurrence and characteristics of all the other clouds through its effect on the large-scale atmospheric conditions. The net effect is therefore not given by the direct effect of some “average” cumulus cloud in the ensemble. The essence of this scaling problem is (a) the existence of a spectrum of clouds of differing characteristics, and (b) the existence of feedback between the clouds and the large-scale environment. In spite of the complexity of this scaling problem, Arakawa and Shubert (1974) developed a parameterization that accounts for the mutual interactions of an ensemble of cumulus clouds.

A fourth scaling problem with respect to clouds arises from the fact that cloud albedo and emissivity depend nonlinearly on the vertically integrated cloud liquid or ice water content (LWC), and LWC can vary substantially within a GCM grid cell. Cloud feedbacks on climatic change depend on how LWC changes with climate and on the rate of change of cloud albedo and emissivity with LWC. Because of the nonlinearities involved, computation of the net cloud feedback using the mean cloud LWC and using a probability distribution of LWCs will yield different results, even for the same grid-mean change in LWC, if the within-grid cell variation in LWC is sufficiently large. Considine et al. (1997) present the first step in the development of a parameterization for the spatial variability of LWC in marine boundary layer clouds. The development of such a parameterization requires some hypothesis about the mechanisms causing spatial variation.

Given that mesoscale motions depend on the typical spatial extent of surface heterogeneities, as well as on the larger scale atmospheric conditions, it might be possible to parameterize the effects of mesoscale motions.

Simulating the impact of widespread deforestation

In assessments of the climatic impact of deforestation using climate models, the deforestation has been applied to entire model grid cells. Deforestation in reality proceeds as a growing patchwork of deforested areas, with secondary regrowth on abandoned patches (O'Brien, 1996). As noted in the review by Pielke and Avissar (1990), the juxtaposition of transpiring vegetation next to dry, bare land can generate circulations as strong as sea breezes. Given the importance of spatial variability in surface characteristics at a scale of a few kilometers to mesoscale motions, and the likely importance of mesoscale motions to the larger scale flow, the large-scale effects of deforestation could very well depend on the small-scale structure of deforestation.

The large-scale effects of deforestation could very well depend on the small-scale structure of deforestation.

Net photosynthesis and the response of ecosystems to higher atmospheric CO2

The net flux of carbon between plants and the atmosphere is closely associated with the vertical fluxes of heat and moisture, and a number of land surface models have been developed which simulate these coupled fluxes in an internally consistent manner (Bonan, 1995; Hunt et al. 1996; Sellers et al. 1996). Some of these models have been used to evaluate the present-day global distribution of net photosynthesis using a lumped approach, namely, applying leaf or canopy-scale relationships to grid squares 1° x 1° in size or larger (Hunt et al. 1996; Zhang et al. 1996). Pierce and Running (1995) assessed the errors incurred in using the lumped approach to estimate average net primary productivity (NPP) over an area of 110 km x 110 km in western Montana (about 1° x 1°). The effects of averaging the smaller scale variation in climate, topography, leaf area index, and soil water holding capacity were determined by comparing the lumped results with results obtained with a distributed model. The lumped approach gave areal-mean NPP that differed by 15 to 30 percent from the distributed approach, depending on the season.

In the case of the photosynthetic response to higher CO2, a scaling problem arises in four distinct ways. The first is the usual problem of spatial heterogeneity combined with nonlinearity, but here, there is important variation in the vertical, involving leaf temperature, nitrogen content, and the availability of light. Reynolds et al. (1992) investigated the importance of these effects using a multi-layer canopy model of scrub oak in effect, a deterministically distributed model. They found that substantial errors in the absolute carbon and water vapor fluxes can occur using a single-layer model for either present or doubled CO2, but that the relative response of an entire plant to a CO2 doubling differed little between distributed and lumped models.

The second way in which scaling of the photosynthetic response can be problematic is through feedback between the plant and the surrounding environment. If a higher CO2 concentration leads to a greater leaf area in the upper canopy layers, this will reduce the availability of light in lower canopy layers, and the response of the entire canopy will not be equal to the scaled response of an individual leaf. Feedback between the leaf and canopy scales has been shown to be important in modulating the response of evapotranspiration, at the scale of the canopy, to increasing CO2. At the scale of the leaf, higher CO2 tends to reduce evapotranspiration because it leads to partial closure of the stomata. However, in ecosystems such as closed forests, where the vegetation strongly influences the air humidity next to the plant, the effect of stomatal closure in all the leaves of the canopy is to reduce the canopy humidity, thereby tending to drive evapotranspiration rates back up (Jarvis and McNaughton, 1986).

The third way in which scaling can be problematic is as a result of feedback or interactions between different plant components. The initial stimulation of photosynthesis at the scale of

the leaf leads to changes in the allocation of carbon and nitrogen to roots and shoots, which then feed back to the leaves and alter the photosynthetic response at the scale of the plant. However, in a case studied by Reynolds et al. (1993), these feedbacks reduced the plant-level photosynthetic response by only 10 percent compared to the long term leaf-level response.

A fourth consideration that gives rise to a scaling problem is that an atmospheric CO2 increase will not have the same relative effect on photosynthesis or water use in all species. Consequently, the interactions among species will be altered, thereby precluding a simple upscaling.

The response of forests to climatic change

The response of land plants to climatic change has been assessed using a variety of different approaches, and prominent among these different approaches has been the use of "gap" models which simulate the competition between different plant species within a small (about 10 m2) patch. All except the very most recent gap models assume the immediate availability of seed stock for all the species that could potentially grow in a given region. If these models were applied simply to evaluate the response to isolated disturbances in a restricted region, this would be an adequate assumption. However, when modeling continental-scale ecological responses to continental-scale climatic changes, this assumption is inappropriate because of the lag that would occur in reality between the time when the climate becomes appropriate for the growth of a species not currently found nearby, and the arrival of seeds from the closest initial occurrence of the species in question. Thus, a scaling problem arises due to the increasing importance of temporal lags as the spatial scale over which a response must occur increases.

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Terrestrial and marine ecology

A number of upscaling issues arise in terrestrial ecology pertaining to the distribution of plants and animals. Among these issues are (a) the changing importance of different controlling variables at different scales; (b) the dynamics of heterogeneous landscapes, in particular, the role of interactions between adjacent landscape units and of landscape connectivity; and (c) the relationship between disturbances and the large-scale ecosystem structure.

The relative importance of different variables in explaining species distributions changes with scale, so observations at a small scale might not correctly identify the dominant processes that generate the large-scale pattern (Root and Schneider, 1995). Ecosystem models that operate at only one scale are not likely to incorporate mechanisms properly. This implies that prediction at the local scale must take into account local processes and their modulation by larger scale variables. Unless the correct processes are identified and properly represented, large-scale ecological impact assessments will be in error. A general problem in linking across scales is to determine the extent to which fine-scale detail can be neglected. Some detail is just noise, but in other cases, emergent phenomena can arise from the collective behavior of small-scale processes (Levin, 1992).

Spatial heterogeneity combined with dispersal alters the dynamics of species interactions in a number of ways (Levin, 1976). Hence, the response of animal species to climatic change will involve interactions between adjacent landscape units, as well as direct biotic-abiotic relationships at a fine-scale. This in turn implies that the heterogeneity of the landscape is important to the response, as also argued by Pickett and Cadenasso (1995). The input-response relationship is therefore likely to be different than that expected based on small-scale considerations alone.

Landscape connectivity a particular attribute of spatial heterogeneity is also crucial to species and their response to climatic change. Even in the absence of climatic change, connectivity is critical inasmuch as the survival of populations depends on the rate of local extinctions (within patches) and the ease of movement between patches (Turner, 1989). The importance of connectivity will be amplified when rapid shifts in climatic zones occur (Schwartz, 1992). Thus, knowing only the proportion of different landscape types within a GCM-size grid cell is not sufficient for predicting impacts.

The large-scale impact of climatic change will likely depend on the spatial (and temporal) scales of disturbances and on the interaction between disturbances and the small-scale structure of landscape variability. Turner et al. (1993) show how the spatial and temporal scales of disturbance influence the large-scale statistical properties of a landscape (for example, the proportions of the landscape in different successional stages). Conversely, the effect of a change in the disturbance regime, and how individual disturbances propagate, depends on the spatial arrangement of patches that are susceptible or resistant to disturbances (Turner et al., 1989). Landscape heterogeneity can enhance or retard the spread of disturbances. Thus, the impact of changes in large-scale climatic parameters, which alter the disturbance regime, will depend on subgrid-scale landscape variability.

To what extent can fine-scale detail be neglected? Some detail is just noise, but in other cases, emergent phenomena can arise from the collective behavior of small-scale processes.

Physical oceanography and sea ice

The global-scale ocean circulation depends on mixing processes occurring at a scale of 1 meter. This was first shown by Bryan (1987), who demonstrated, using a 3 -dimensional ocean GCM, that the intensity of the thermohaline overturning circulation depends on the value of the subgrid-scale diffusion coefficient. This coefficient , which is a prescribed parameter in ocean GCMs, is meant to represent the effect of vertical mixing processes that have a typical scale of 1 m. Diffusion is also used to represent the effects of horizontal mixing, but in this case the mixing involves eddies with a spatial scale of about 50 km. In both cases, the diffusion parameterization is an implicit upscaling that assumes the existence of an emergent property.

Two distinct scaling issues arise in the treatment of sea ice: (a) how the dynamic behavior of sea ice changes with scale, and (b) determination of the scale at which atmospheric forcing of sea ice motion is most directly applicable (Overland et al., 1995). An aggregate of ice floes behaves in ways that are quite different from the behavior of individual ice floes; in particular, ice behaves like a granular medium at the 0.1-1 km scale, while at a regional scale it behaves like a viscous fluid. Furthermore, the local velocity of sea ice cannot be directly related to the local atmospheric shear stress. Rather, the valid linkage is between regional atmospheric forcing and regional sea ice deformation. However, atmospheric forcing varies much more rapidly in time than the sea ice response, so the history of atmospheric forcing must also be taken into account.

Atmospheric chemistry

Scaling problems arise in the atmospheric chemistry of compounds that have a very short lifespan in the atmosphere, which results in strong spatial variations in their concentration, and where the reaction chemistry depends highly nonlinearly on concentration. The main difficulty involves NOx gases (NO and NO2), which have highly concentrated emission sources and have a lifespan of only a few days. Even fairly high resolution models (60 km x 60 km) cannot adequately represent the range of concentrations encountered in nature, so that significant errors in the projected impact of emission changes can still occur. An alternative to the computationally expensive approach of going to very high resolution in a global model is

to compute the impact of changes in the emissions of a variety of pollutants for representative chemical conditions (e. g., clean continental, polluted continental, clean maritime, and polluted maritime), without trying to integrate globally, as in Thompson et al. (1990). This amounts to a refusal to perform upscaling, but still yields policy-relevant information.

Economics

The main concerns of economics with regard to global environmental change pertain to (1) estimating the costs of actions taken to prevent or minimize environmental changes, and (2) estimating the costs of environmental changes.

The costs of greenhouse gas emission abatement can be assessed at the project, sectoral, or macro-economic scale. If costs are first estimated at the project level, then there is a need to scale up these costs by aggregating over the whole range of projects that could be undertaken in a sector or economy. This is the classical "bottom-up" approach, and entails comparing the lifecycle costs of currently used technologies and new, more efficient technologies that could be used in their place. These cost assessments depend on the prevailing (or projected) prices of energy, technology, and labor. The costs estimated for individual firms or projects cannot, however, be simply aggregated. This is because the implementation of efficiency measures by a single firm cannot noticeably affect the price of energy or of other factors, but if a large number of individual firms (and consumers) implement energy efficiency (or fuel switching) measures, this can be expected to noticeably influence prices and hence the ultimate reductions in emissions of greenhouse gases that are achieved. Thus, a scaling problem arises because of feedback between the small and large scales. This scaling problem is analogous to that of extrapolating the response of evapotranspiration (to a change in atmospheric CO2) from an individual leaf to a forest canopy.

An aggregate of ice floes behaves in ways that are quite different from the behavior of individual ice floes; ice behaves like a granular medium at the 0.1-1 km scale, while at a regional scale it behaves like a viscous fluid.

At the other end of the scale spectrum is the "top-down" approach, in which economic correlations derived at the national scale are used in models of a national or the global economy. Top-down models do not involve upscaling in the sense of having to link processes or relationships derived at a small scale and applied at a larger scale. Rather, they are based on direct observations at the larger scale. However, when top-down models are used in a predictive mode under entirely different circumstances than in the past (as indeed they are), there is an implicit upscaling. This is because the large-scale response to a change in price involves the integrated effect of a large number of small-scale actions, and this integration is assumed when large-scale price-response relationships are used. Potential error arises in that a different set of detailed response options could come into play in the future. For example, there could be a greater role of non-price induced improvements in efficiency or fuel switching due to partial removal of barriers to energy-efficient investments by government action. The preferred solution to what can now be recognized as an upscaling problem is to provide enough detail that processes (response option) at the next lower level in the economic model hierarchy can be explicitly represented.

On the other hand, some of the potential costs of greenhouse gas abatement can be assessed only at scales beyond some minimum scale of analysis. These include costs related to shifts in investment patterns and changes in the rate of growth of productivity of labor and capital. Other scaling issues concern the question of whether there are economies or diseconomies with increasing scale, and the aggregation of risk.

With regard to the costs of environmental changes, the key upscaling issue is how to correctly integrate impacts across sectors and how to aggregate individual valuations of costs that are not reflected in market prices.

Political Science

Political scientists have analyzed human-environment interactions at two scales. One is at the scale of small, stateless societies, while the other is at the international scale of nation states. Political scientists have found that the "tragedy of the commons" often does not occur in societies that lack a strong or any central control, and considerable attention has been devoted to explaining how self-interested actors are able to use resources sustainably in the absence of an overarching authority. This may present a useful analog to the problem of devising schemes for the international regulation of global resources by nation states, for which an overarching authority is also absent, if the insights gained from small-scale analysis can be applied to the global scale.

With regard to the costs of environmental changes, the key upscaling issue is how to correctly integrate impacts across sectors and how to aggregate individual valuations of costs that are not reflected in market prices.

At the international scale, political scientists have found that relations often do not conform to the non-cooperative logic of the prisoner's dilemma. Political scientists working at this scale try to understand the basis for sustained cooperation for a range of analytically distinct situations. Young (1994) indicates that there is a need to closely compare the local and international streams of analysis, and he presents some initial conclusions concerning the applicability and/or roles of pre-negotia, monitoring, and transparency at the local and international scales.

Synthesis

The preceding discussion is summarized in Table 1.1, which classifies upscaling problems in global change research according to the underlying fundamental cause, and in Table 1.2, which summarizes the solutions adopted.

Danny Harvey sums up with Bill Gough, Karen O'Brien and Marv Waterstone (photo by Susan Hassol).

Fundamental Cause	Examples
Spatial variability + process nonlinearity	Surface hydrology, formation of clouds and precipitation, photosynthetic response to higher atmospheric CO2
Minimum spatial scale required for certain process	Runoff generation
Different processes dominate at different scales	Terrestrial and marine ecology
Feedbacks between scales	Transpiration response to higher CO2, Economic costs of greenhouse gas emission abatement
Development of emergent properties	Sea ice
Edge effects	Sea ice, terrestrial ecology
Temporal lag dependent on spatial scale	Response of ecosystem species composition to climatic change
Collective response with differential effects	Ecosystem response to higher CO2, Societal valuation of impacts

Table 1.1
A classification of upscaling problems based on the underlying fundamental cause.

Solution	Examples
Ignore	Surface hydrology, surface-air fluxes
Use a distributed model	Surface hydrology, surface-air fluxes
Use a lumped model with effective parameter values	Surface hydrology, surface-air fluxes
Parameterize interactions between distinct patches	Effects of mesoscale motions in the atmosphere
Parameterize small-scale details	Diffusion approximation
Create a new model to integrate effects of next smallest scale	Cumulus cloud ensembles, Ecophysiological models
Greatly increase model resolution	Ocean GCMs
Refuse	Tropospheric chemistry

Table 1.2
Solutions to upscaling problems that arise in modeling of physical and biological processes.

A common reason for an upscaling problem is the existence of spatial heterogeneity combined with nonlinearities in the relevant processes.

Causes of Upscaling Problems

A common reason for an upscaling problem is the existence of spatial heterogeneity combined with nonlinearities in the relevant processes. This problem arises in surface hydrology, the computation of surface-air fluxes of heat and water vapor, in plant physiological processes, in cloud dynamics, and in atmospheric chemistry. However, there are a number of other, conceptually distinct, reasons why upscaling problems arise.

First, it has been widely observed in marine and terrestrial ecology that different processes are primarily responsible for producing the spatial distribution of plants and animals at different scales. The same is also true with regard to human land use patterns, and for the driving factors for population growth and migration. This implies that correlations derived at one scale might not be applicable at a larger scale or to changes through time. It also implies that the simplification to a model (such as exclusion of certain processes or interactions) that is acceptable at one scale may not be acceptable at a different scale (this of course is well known in fluid dynamics).

Emergent properties arise from the mutual interaction of small-scale components, whereas the feedback causation involves interaction between small-scale components and larger scale variables.

Second, feedbacks can occur between the small-scale components of a system and the larger scale. This has the net effect of altering the relationship between large-scale driving factors and the aggregate response of the system. Thus, the response of transpiration from a leaf and ultimately from an entire forest canopy to changes in atmospheric CO2 concentration is strongly modulated by the effect of transpiration on the relative humidity within a forest canopy. Similarly, the effect of a change in energy prices (through a carbon tax, for example) on energy use at the scale of an individual firm and ultimately for an entire national economy is modulated by the feedbacks of energy demand on the price of energy.

Another conceptually distinct cause of an upscaling problem is the development of emergent properties. Emergent properties arise from the mutual interaction of small-scale components among themselves, whereas the feedback causation (discussed above) involves interaction between small-scale components and larger scale variables. The most striking example of the development of emergent properties is in sea ice, where the mutual interaction of individual ice floes imparts properties (such as viscous behavior) at the large scale which are not found in any of the constituent components.

The emergent properties that arise with increasing scale in sea ice depend largely on interactions at the edges between ice floes. Edge effects are also important to the dynamics of terrestrial ecosystems at larger scales. The edge effects in this case occur between landscape patches with different characteristics. The larger scale ecological characteristics (such as overall species diversity) also depend on dispersal from one patch to surrounding patches, so that both spatial heterogeneity and the characteristics (such as speed) of the dispersal process are critical to the system statistical properties and dynamics at the larger scale. To the extent that the ecosystem properties at the larger scale are different from those at the patch scale and depend on the mutual interaction between different patches, this provides another example of the occurrence of emergent properties as we scale up.

An upscaling problem can also arise when there is a temporal lag in the response of a system to a perturbation, if this lag increases the larger the spatial scale over which the adjustment to the perturbation must occur. A clear example is in the response of forest species composition to large-scale climatic change, when the climatic change is so large that the climate becomes suitable for species whose seedlings are not currently available at a given site. Correct modeling of the time-dependent response at a given site requires scaling up to a large spatial scale so that the gradual dispersal of species into new regions can be modelled.

Finally, aggregating environmental values and the costs of climatic change across individuals to the scale of a society presents upscaling problems for yet different reasons. A key issue here is to determine how to weight different values and costs when aggregating to the larger scale; the choice of weighting scheme contains implicit assumptions concerning the distribution of income, and depends on ethical judgments something that is not always explicitly

acknowledged. The only thing that one can say with confidence is that the least defensible weighting is a uniform weighting, yet this is exactly what has been done in many cases. One can draw an analogy to the computation of effective parameter values for use in lumped models of physical systems; the correct effective value is usually anything but a uniform weighting of the individual values, and the correct weighting often changes with the conditions.

Solutions to Upscaling Problems

The solution adopted when upscaling is required depends in part on the underlying reason for the particular scaling problem in question. The first solution, which is not always a solution, is to ignore the problem. This is done, for example, when point process models are applied to an entire GCM grid cell without modification, or when estimated costs of climatic change are simply summed over all members of a society. In some cases this can be an acceptable approach, if the underlying nonlinearities are weak or if they fortuitously cancel. The task in this case is to determine the conditions under which the upscaling problem can be ignored.

In weighting different values and costs when aggregating to the larger scale, the least defensible method is a uniform weighting, yet this is exactly what has been done in many cases.

The second solution is to use a distributed point process model, whereby processes are computed for a number of distinct patches within a region, and the results summed. This is an acceptable approach for dealing with scaling problems that arise due to spatial heterogeneity combined with process nonlinearity, but is not valid when there are interactions between adjacent patches. An alternative approach is to apply the process model to the entire heterogenous domain but to use effective parameter values that account for the heterogeneity. A problem with this approach is that the relationship between the distribution of real parameter values and the effective parameter value can depend on the state of the system, and thus can change over time.

Where interactions between patches are important, it is necessary to either directly parameterize these effects, or to create a whole new model which incorporates these interactions and their effects. The parameterization approach can be used when the details of small-scale interactions do not matter. The simplest example is the diffusion parameterization to represent the effects of turbulent mixing or the random dispersal of plants and animals. The diffusion approximation works at scales where the unpredictability of specific events cancels out, and the overall statistical properties can be relied upon. A more complicated example is the parameterization of the effect of organized mesoscale motions on vertical heat fluxes. This is a case involving interactions between adjacent land surface patches, inasmuch as rising motion over one patch affects the tendency for rising or sinking motion over adjacent patches. In the case of cumulus cloud ensembles, in which feedbacks between the large-scale environment and the ensemble occur, but which also involve strong interactions between the members of the ensemble, rather complicated parameterizations have been developed which bear little resemblance to earlier parameterizations that considered only a single cloud interacting with its environment. Models of species diversity and the spread of disturbances also explicitly consider interactions between adjacent patches.

When spatial upscaling involves the integration of different components from one level within a system hierarchy to a higher level, the preferred approach is to link mechanistic models of the individual components, as discussed by Reynolds et al. (1993). For example, a model of plant growth would link modules involving shoot biomass, root biomass, and carbon and nitrogen substrate pools. The submodules themselves should be based on phenomenological relationships (i. e., relationships based on a fundamental understanding of the processes involved, rather than being purely empirical) and parameterized with data collected at that level. The model

would then be validated against data collected at the scale of interest and constrained by data at larger scales. Models that include mechanisms across a wide range of levels should be avoided because, as discussed by Reynolds et al. (1993), they tend to be very complex, unstable, and difficult to verify and alter.

These principles can also be applied to the question of estimating the cost of greenhouse gas emission reduction measures at the scale of a national economy. As in models of sea ice dynamics or in the response of plants to higher atmospheric CO_2 concentration, a model hierarchy can be identified, where different levels in the hierarchy roughly correspond to different spatial scales. Here, the lowest level in the hierarchy consists of models (and measurements) of the energy use by specific technologies (e. g., motors and commercial chillers). The next level up consists of models of individual buildings or industrial processes, where the integrated effect of individual technologies on the energy use at the scale of the building or industrial plant can be assessed. These provide estimates of cost-effective energy saving potential at the scale of the individual firm, the scale at which bottom-up assessments typically begin. The next level up consists of models of an entire sector or of a national economy. Based on the principle in hierarchy theory that assessments at level n should be based on the integration of models from level n-1 (O'Neill, 1988), national level assessments should be based on the integration of models at the next lower level, which involves individual energy end uses and energy supply choices. That is, considerable bottom-up detail needs to be built into top-down models if they are to be credible, and this is now being done to an increasing extent.

When spatial upscaling involves the integration of different components from one level within a system hierarchy to a higher level, the preferred approach is to link mechanistic models of the individual components.

The next-to-last solution to the upscaling problem that has been considered here is to simply run a model at a fine enough resolution that the important processes can be explicitly represented. This approach has been used with some success in ocean GCMs to account for the effects of mesoscale (50 km) eddies on the large-scale flow. This has also been tried in models of tropospheric chemistry, but does not entirely work because strong variations in the concentrations of important chemical species can occur inside grid cells as small as 50 km x 50 km. An alternative in this case is to compute changes for different representative chemical regions but without attempting a global integration what is termed "Refuse" in Table 1.2.

Research Questions and Needs

Upscaling is widely required in models used to predict or understand global environmental change. An upscaling problem can arise for a variety of conceptually distinct reasons, and a number of distinct solutions have been applied to this problem. Greater recognition of the existence of upscaling problems by researchers across the spectrum of disciplines involved in global change research should, hopefully, lead to the formulation of better models for purposes of analysis and prediction. At the same time, it should lead to greater appreciation of the weaknesses of current approaches.

For this to happen, a number of specific research needs will have to be addressed. In the physical and biological sciences, these research needs are as follows:

(1) There is a need for information on the spatial variability that exists within 1° x 1° grid cells on a global basis. This is needed for parameters such as soil moisture holding capacity, soil infiltration rate, vegetation type, and leaf area index. In order to adequately characterize the probability distribution functions, information on means, variabilities, and skewness is required. Information is also needed on the spatial co-variation among variables.

(2) The conditions under which a lumped approach can be used instead of a distributed model approach need to be thoroughly investigated.

(3) For conditions in which a distributed approach is required, work is needed to determine which variables needed to be represented in a distributed manner and which can be safely averaged.

(4) When a statistically distributed model approach is used and the probability distribution functions could themselves change as large-scale conditions change, the ways in which they might change and the extent of such potential changes need to be determined. This is a possible problem in cloud modelling in particular, but it is unlikely to be a problem in the modelling of surface hydrology.

In both the biological and social sciences, an important area for further research is to determine ways to properly compare studies that were carried out at different scales. Levin (1992, p. 1953) raises the possibility that scaling laws can be developed (in ecology, at least) that allow such comparisons. There is scope for considerably more work on upscaling in all disciplines involved in global change research, but the greatest challenges may very well lie in the modeling of land-atmosphere-cloud interactions.

Greater recognition of the existence of upscaling problems should, hopefully, lead to the formulation of better models for purposes of analysis and prediction.

The need for upscaling has mixed implications for our ability to correctly predict changes at the model grid scale and larger. First, in cases such as soil moisture and precipitation, our ability to correctly predict changes in these variables at the grid scale improves as the simulation of the present conditions improves (see, for example, Meehl and Washington, 1988). Inasmuch as correct upscaling alters the grid -mean simulated values for the present climate, and generally improves the simulation, it will improve our predictability. On the other hand, if the probability distribution functions or parameterized interactions between units used in the upscaling algorithm are themselves subject to change as the climate changes, then predictability will worsen if these changes cannot be correctly anticipated.

In closing, it seems reasonable to believe that much of the information needed to improve our upscaling techniques could also help in dealing with the complementary scaling problem, which is not addressed here that of downscaling from grid-average output data to specific points within the grid. Downscaling techniques are reviewed in Bass and Brook (1997). In particular, much of the data that will need to be collected in order to construct probability distribution functions for surface and vegetation properties can, if also retained in a spatially distributed form, be used for downscaling.

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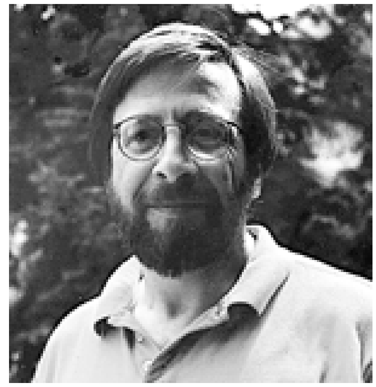
Much of the information needed to improve our upscaling techniques could also help in dealing with downscaling from grid-average output data to specific points within the grid.

Forward to Next Section//Back to Table of Contents//AGCI Homepage//Comments: agcimail@agci.org

At What Scales Does Landscape Heterogeneity Impact Climate?



Roni Avissar

Rutgers University
New Brunswick, New Jersey

Avissar discussed the impacts of landscape heterogeneity on atmospheric turbulence, mesoscale circulation, clouds, and precipitation and presented an approach for representing these effects in global models. Atmospheric effects from landscape heterogeneity are examined at three scales: the microscale, defined as up to 2 kilometers, the large scale, above 2000 km, and the mesoscale, which is between the microscale and the large scale.

To understand the effects of landscape heterogeneity on the atmosphere and recognize which are the most important processes and interactions, we begin by asking which land-surface parameters are of greatest importance for atmospheric models. The method used to answer this question is the Fourier Amplitude Sensitivity Test (FAST) with Land-Atmosphere Interactions Dynamics (LAID). FAST is a very efficient and powerful technique for determining the relative contribution of the distribution of individual input parameters (assuming that their exact value is unknown) to the variance of the model output. By simultaneously varying all parameters according to their individual probability density functions, the number of computations needed is very much reduced by this technique.

This technique was used to obtain the most important land-surface characteristics for forcing climate. Results of this analysis indicate that for vegetated land, stomatal conductance and surface roughness are the two most important characteristics for forcing the atmosphere. For bare land, soil-surface wetness and surface roughness are most important. Leaf area index (LAI) is another important parameter as it indicates the relative amounts of vegetation and bare ground. Albedo can also play a significant role in certain circumstances. It is important to point out that this analysis does not offer a priority list for all situations. Different parameters are important under different atmospheric conditions. In addition, this analysis assumes that parameters are independent, whereas in reality, they are related.

For vegetated land, stomatal conductance and surface roughness are the two most important characteristics for forcing the atmosphere. For bare land, soil-surface wetness and surface roughness are most important.

Microscale Heterogeneity Patchiness

What is the impact of the spatial variability of the most important land-surface parameters on land-surface heat fluxes? The method used to address this question was the Patchy Land-Atmosphere Interactions Dynamics (PLAID) technique of Avissar and Pielke (1989). In this “mosaic approach,” different subgrid surface types are treated as different “tiles” in a grid “mosaic.” This assumes that the horizontal fluxes between different types of vegetation in the landscape are not important. Each system is resolved independently, and then an areal average of these is used to calculate the fluxes that come from the grid. This method is only useful for scales up to 5 to 10 km; at scales larger than this, the atmospheric boundary layer dynamics are affected by land-surface heterogeneity, and this method may not be correct. The major conclusion from this work is that except for albedo, which relates more or less linearly to the

surface heat fluxes, the spatial variability of the four other parameters (stomatal conductance, surface roughness, leaf area index, and soil-surface wetness) should be considered to avoid significant errors; using a mean value, as opposed to using the entire distribution, introduces errors as large as 100 watts per square meter.

Microscale Heterogeneity: Large-Eddy Simulations and Lidar Observations

Shifting the focus from small eddies to the effects of large eddies, Avissar discussed the impact of microscale spatial variability of surface sensible heat flux and topographical features on the atmospheric boundary layer. He described Large-Eddy Simulations (LES), a three-dimensional model used at a very fine resolution (on the order of 100 meters) to resolve the large eddies of turbulence. It is well known that the most energetic turbulent eddies have a typical size on the order of 800-1000 meters, and this type of model is designed to resolve these eddies. This is a powerful technique but the high resolution makes it impractical to run more than one diurnal cycle. The resolution is very fine at the ground surface (5 meters) and becomes coarser further away from the surface, so at about 200-300 meters above the surface, the resolution is about 100 meters.

As long as the characteristic length scale of heterogeneity is smaller than 5 to 10 km, and the topographical features are smaller than about 200 meters, there is no significant impact on the mean characteristics of the convective boundary layer.

In this study, the LES version of the Regional Atmospheric Modeling System (RAMS) is used. Avissar emphasizes the importance of this work because it indicates when the spatial heterogeneity triggers processes or mechanisms that make it incorrect to assume horizontal homogeneity. The key conclusion from this study is that as long as the characteristic length scale of heterogeneity is smaller than 5 to 10 km, and the topographical features are smaller than about 200 meters, there is no significant impact on the mean characteristics of the convective boundary layer.

For validation of this numerical model, Avissar presented observations from FIFE (the 1980s Kansas field experiment). He presented an image from a scanning LIDAR (a light detection and ranging instrument) which shows backscattering from aerosols in the boundary layer (see Figure 1.3 below). This image reveals the structure of turbulent eddies in the atmospheric boundary layer by showing the aerosols transported by those eddies. Power spectrum techniques and spatial and temporal auto correlations are used to discern if the model properly represents this spectrum of turbulence. The LIDAR image shows that eddies on the scale of 800 meters are those with the most energy in the atmosphere. Auto correlations reveal that the lifetime of eddies in the convective boundary layer is roughly ten to fifteen minutes.

Numerical Experiments

Parameterizations of the land surface are very controversial. An intercomparison experiment revealed that even models based on the same concepts had large differences in results when they used different parameterizations of soil moisture in particular. To avoid these drawbacks and focus instead on the dynamics of the atmosphere, Avissar and colleagues forced a model (RAMS-LES) with the spatial distribution of fluxes (diurnal variations of the latent heat flux, heat conducted from ground, and sensible heat flux) from a network of surface observations. In the area observed, the maximum difference in topography is only 100 meters. Results from three simulations indicate that with topographical features of up to 200 meters, there is no effect on the mean properties of turbulence in the boundary layer. The topography is not important to the strength of the eddies but rather simply serves to anchor them. But with topographical differences of more than 200 meters, the mean properties of turbulence and kinetic energy in the boundary layer are significantly affected by landscape heterogeneity.

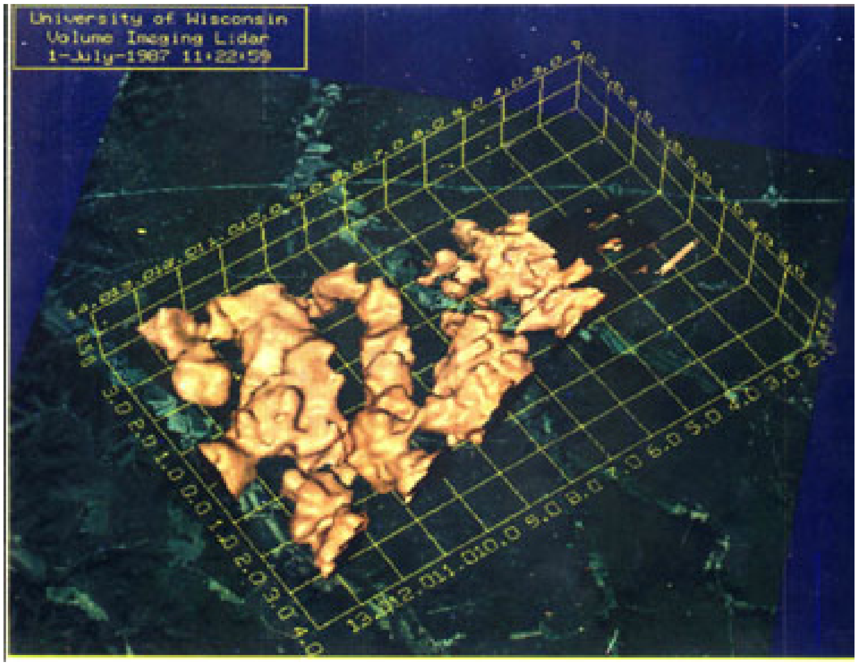


Figure 1.3

This LIDAR image reveals the structure of turbulent eddies in the atmospheric boundary layer by showing backscattering from the aerosols transported by those eddies.

With topographical differences of more than 200 meters, the mean properties of turbulence and kinetic energy in the boundary layer are significantly affected by landscape heterogeneity.

There is a need to better parameterize eddies as they decrease in size below 100 meters. The current subgrid-scale parameterization does not do a very good job at dissipating eddies. Such an improvement is under development in Avissar's research group and he is optimistic about its success.

The next step is to use this model to determine at what point the dynamics of the atmosphere are altered by landscape heterogeneity. To do this, the model is forced with different amplitudes and wavelengths of heat fluxes. Results show that the distribution of heat flux in the boundary layer is a straight line in homogeneous terrain. But in heterogeneous terrain, with 20 or 40 kilometer waves present, turbulent kinetic energy is very strong close to the ground surface and also very strong close to the top of the boundary layer. This emphasizes that the eddies are organizing in circulation which has a strong component close to the ground surface and near the top of the boundary layer. Results also indicate that this process is nonlinear, and depends on the intensity of the mean heat flux fueling the boundary layer.

Avissar then showed a wavelet analysis of the results, which is similar to a Fourier analysis but has the advantage of showing the location of the different eddies. The key result of this analysis is that a gap is found between the microscale and mesoscale eddies, emphasizing the possibility of making an objective separation of scales. This has significant implications for the design of atmospheric models and subgrid-scale parameterizations.

In addition, when the mean heat flux is relatively small, the horizontal scale of the wavelength impacts the atmosphere much more significantly than when the mean heat flux is high. The ratio between the contribution to turbulent kinetic energy by buoyancy and by the horizontal pressure

gradient seems to be a useful dimensionless quantity for the development of an appropriate parameterization of these effects. The more significant the buoyancy, the more difficult it is for horizontal structure to develop in the boundary layer.

Mesoscale Heterogeneity: Numerical Modeling

Moving to much larger scales, what is the impact of mesoscale spatial variability of surface heat fluxes and topographical features on the atmosphere? In sum, results indicate that mesoscale discontinuities considerably affect the vertical profile of mean atmospheric variables, heat fluxes, clouds, and precipitation. These effects should be parameterized in GCMs. Mesoscale perturbations create atmospheric dynamical processes that can be extremely important.

Eddies are organizing in circulation which has a strong component close to the ground surface and near the top of the boundary layer.

Avissar discussed an upcoming field experiment in Rondonia which he believes will be very important in helping to improve parameterizations of mesoscale effects in GCMs. A satellite image of the study area reveals the fishbone pattern of deforestation and development along roads which is a characteristic pattern of the expansion of human activity in tropical forests. Two types of heterogeneity are apparent: microscale heterogeneity on the order of a few kilometers and mesoscale heterogeneity on the order of 300 km by 200 km. In addition, the natural topography varies from sea level up to 1100 meters. Despite these large variations, GCMs assume a flat domain with one big leaf covering the whole area; thus, one cannot expect the results of such models to fit reality.

In preparation for this field experiment, numerical simulations have been conducted to assess the effects of microscale and mesoscale heterogeneity on clouds and precipitation. The dynamics of circulation in these simulations are based on results from the LES; the only parameterizations used are for cloud microphysics. Five different domains are used to consider combinations of different types of heterogeneity. Results for accumulated precipitation over these different domains after one day indicate that over homogeneous pasture, there is virtually no precipitation. Over homogeneous forest, there is a random distribution of precipitation cells, which is not surprising because turbulence is the dominant forcing mechanism, and it has a random structure. When there is landscape heterogeneity, it strongly affects the distribution of precipitation. At the microscale, landscape organizes precipitation but does not add to the total amount of water. However, mesoscale landscape heterogeneity significantly increases precipitation, which is well organized according to the heterogeneity.

Another important note is that current GCMs parameterize only one of the two important processes simulated in this experiment. They parameterize the effects of the turbulent heat fluxes which are dominant closer to the surface but fail to include mesoscale heat fluxes, which are dominant in the middle and upper part of the boundary layer. This is a major problem, Avissar says, because the effects of the mesoscale fluxes are much greater and must be parameterized to make the GCMs better simulate reality.

Omitting these effects has a very significant impact on the results of GCMs. Account for these heterogeneous effects over all of Earth's land surface is as important as doubling the carbon dioxide concentration in a GCM (on order of 2°C), Avissar says. The landscape causes perturbations to the system that can affect large scale atmospheric circulation patterns. Roger Pielke adds that thunderstorms are a key element of this because they develop based on surface considerations and have a disproportionate effect on climate. The landscape tends to organize the total moisture available and this has huge and far reaching climatic effects. One example

of such far reaching impacts, Pielke says, is El Niño, where a local warm ocean anomaly has teleconnections that have climatic effects around the globe.

An Approach to Parameterizing Mesoscale Effects in GCMs

Similarity theory suggests a four step system to parameterize these effects: 1) identify the variables relevant to the problem; 2) organize the variables into dimensionless groups; 3) gather observations or perform experiments to determine their values; and 4) find an empirical relationship between dimensionless groups. Because this approach is based on empirical relations, experiments are needed to provide appropriate data sets. When the Rondonia experiment is complete, such data will exist, but in the meantime, a model is used to create characteristic landscapes, and quantities are derived from resolved parameters in GCMs. There is a need to develop Soil Vegetation Atmosphere Transfer Schemes (SVATS) to parameterize these effects into GCMs. Avissar believes that there is hope for incorporating mesoscale effects into GCM-scale grids but that it will require close collaboration between atmospheric and land surface researchers.

Accounting for these heterogeneous effects over all of Earth's land surface is as important as doubling the carbon dioxide concentration in a GCM.

Conclusions

Complex mesoscale and microscale (turbulent) interactive processes are involved in the development of shallow convective clouds in heterogeneous landscapes. Even though these processes can significantly affect predictions at all time and spatial scales, they are not parameterized in GCMs and other large-scale atmospheric models. A preliminary parameterization was developed based on large-scale atmospheric conditions which are resolved by the large-scale atmospheric model, the variance of surface sensible heat flux, and a characteristic length scale of heterogeneity of the landscape. Research in this area is needed to improve this parameterization. The development of SVATS able to produce such a length scale and variance is needed. The Rondonia experiment discussed above offers a unique opportunity to provide the appropriate data set needed to calibrate and evaluate this type of parameterization.

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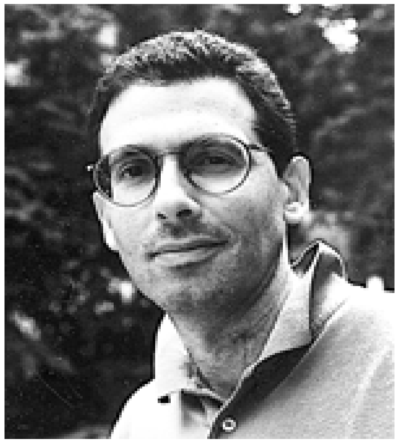

Ecosystem Processes at the Watershed Scale: Scaling from Stand to Region

Larry Band

University of Toronto
Toronto, Canada

As we scale from the level of individual patches to regions, the influence of higher resolution patterns often cannot be ignored.

The flux of energy, carbon and water between the land surface and atmosphere are primary regulators of ecosystem form and function. Landscape to regional level ecosystem productivity, watershed runoff quantity and quality, soil erosion and nutrient cycling and export are influenced by these vertical exchange processes and by the distribution and connectivity of land surface stands or patches. As we scale models or analyses of land surface processes from the level of individual patches to regions, the influence of higher resolution patterns often cannot be ignored due to strongly nonlinear local effects of surface state (within patch effects), and the effects of land surface lateral "circulation" of water (between patch effects). Both of these effects can lead to bias in estimation of mean mass and energy storage and flux variables as we progressively aggregate surface features and lose the effects of both heterogeneity and pattern.

A set of general approaches to scaling or aggregating estimates of surface behavior drawn from small scale models to larger scales have been outlined (Ratstetter et al., 1992, Band et al., 1991):

(1) Aggregation and averaging of surface characteristics with the same model structure (simple aggregation);

(2) Scaling distributions of surface characteristics to larger areas with the same model structure;

(3) Calibrating simpler model structures for larger areas, using selected, small area simulations that are more physically based and verifiable.

Band addressed several key questions regarding these approaches to scaling water and carbon flux and stores from local to regional extent:

(1) When is simple aggregation sufficient for scaling?

(2) Are aspatial probability distribution functions of key surface parameters sufficient for scaling (implicitly assuming key processes are independent)?

(3) To what extent do specific patterns (surface connectivity) of key parameters need to be specified (parameters not independent)?

(4) Are key processes and models formulated and observed at plot scales applicable at larger scales?

Not all of these questions are fully answered at the current time, but they are at the core of the overall uncertainties in applying models developed and tested in small research plots or catchments to large terrestrial surfaces.

Band addressed these questions in reverse order for the case of hydrologic cycling. The current state of the science of hydrology has grown out of two areas of application. The first is an agriculturist tradition where the major driving questions centered on the need for knowing magnitude and timing of irrigation water, thereby requiring a knowledge of soil water budgets. The control volume has been a soil column, typically conceptualized as a one dimensional system with water entering from the soil surface by infiltration or from below by capillarity or ground water rise, and exiting by deep percolation or evapotranspiration. Within the time scale of rainfall or irrigation application, and over topographically flat, homogeneous research plots, vertical head gradients are considered dominant over lateral gradients, such that lateral, within-soil flux could be neglected. Runoff is considered an out put, but typically only in terms of runoff produced by infiltration excess from the surface.

Important terms affecting the movement of water through soil are generally poorly known, highly nonlinear, and show substantial hysteresis.

Generalizing, concepts and models have been applied as local, one-dimensional (1-d) point processes over time. The basic equation used one that underlies most soil hydrology schemes in land surface process models can only be considered an approximation, as important terms affecting the movement of water through soil are generally poorly known, highly nonlinear, and show substantial hysteresis which is not incorporated. In addition, layering of soils and the well expressed lateral variability of water conductivity through soil (which may vary over orders of magnitude within distances of meters), indicates that simple aggregation may not be reliable, and there are strong uncertainties in both parameter estimation for this modeling approach and in being able to validate the model at any scales larger than a soil column.

Water resources engineering has focussed on the generation and routing of river discharge from watersheds, for the impacts on flooding or water supply. This tradition has not required detailed understanding of soil water processes, and has also traditionally considered runoff generation solely as a surface partitioning process. Also generalizing, concepts and models have been applied to storm events, lumping entire catchments into average, or representative states, and often adapting the agricultural soil 1-d model, if a soil model is used at all.

Over the past two decades, more attention has been put into hydrologic problems that require more detailed consideration of the processes by which water enters, moves through and exits hillslope systems. These studies have been motivated by the need to assess the biogeochemistry of terrestrial ecosystems, particularly in response to chronic inputs of natural and anthropogenically-derived pollutants. Advances in soil water measurement techniques has also aided in substantially revising conceptual models of land surface hydrology to account for a wider range of flowpath and flux processes, with the demonstration that a substantial amount of subsurface flow and redistribution may occur both vertically and laterally by non-Darcian flow. It is now standard for watershed models used to estimate and assess runoff generation and surface ecosystem dynamics to make use of the variable source area model, and attempt to account for substantial heterogeneity and redistribution of soil moisture during and between storm events. In this regard, it is interesting that, to date, land surface processes (LSP) models used in conjunction with atmospheric models are still reliant on lumped, 1-d models, although the ability to build in the impacts of small (hydrological) scale redistribution into the resolution of atmospheric models has become a major research focus.

The impacts of conceptual lumping of short spatial scale heterogeneity of soil moisture dynamics on land surface carbon and water exchange have been assessed by a number of researchers (Entekhabi and Eagleson 1989, Band 1983, Famiglietti and Wood 1995, Sellers et al., 1992). Results indicate that simple aggregation may be sufficiently reliable under certain conditions (i. e., either uniformly wet or uniformly dry), but the potential for significant bias exists when the distribution of surface moisture ranges from well-watered to significantly drier conditions spatially. This state is expected to occur during a dry down when a certain portion of the land surface is maintained in a wet condition by lateral recharge (e. g., bottomland) while other portions dry by a combination of evapotranspiration and drainage (e. g., uplands). While the results of investigations have been variable, it appears that disagreement results from whether specific tests included system states that include this degree of soil moisture variability.

Simple aggregation may be sufficiently reliable under certain conditions but the potential for significant bias exists when the distribution of surface moisture ranges from well-watered to significantly drier conditions spatially.

This effect is illustrated in three examples using a common modeling framework. RHESSys (Regional HydroEcological Simulation System) incorporates a hillslope hydrologic model for lateral soil water redistribution modified from TOPMODEL (Beven and Kirkby, 1979), with a canopy model for computing surface water, carbon and nutrient budgets, adapted from BIOME-BGC (Running and Hunt, 1993). The model framework includes the ability to aggregate and disaggregate the description of the landscape, while maintaining the ability to statistically represent smaller length scale heterogeneity in key variables when scaling to larger regions (Band et al., 1993, Nemani et al., 1993).

The first example of aggregation effects is from simulation work in a forested mountain catchment in western Montana through a deep summer drought in 1988 (Band, 1993). Soup Creek is a 13 square kilometer catchment with a substantial range of conditions including steep north and south facing slopes and significant soil water gradients, particularly along the forested, south facing slopes (see Figure 1.4).

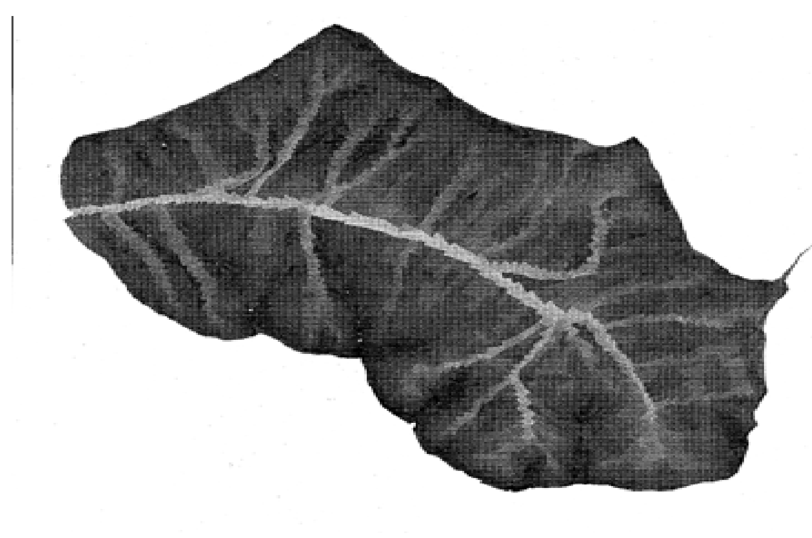

Figure 1.4
The Soup Creek, Montana site with its substantial range of conditions including steep north and south facing slopes and significant soil water gradients. The ridge line is at the center, and darker is wetter.

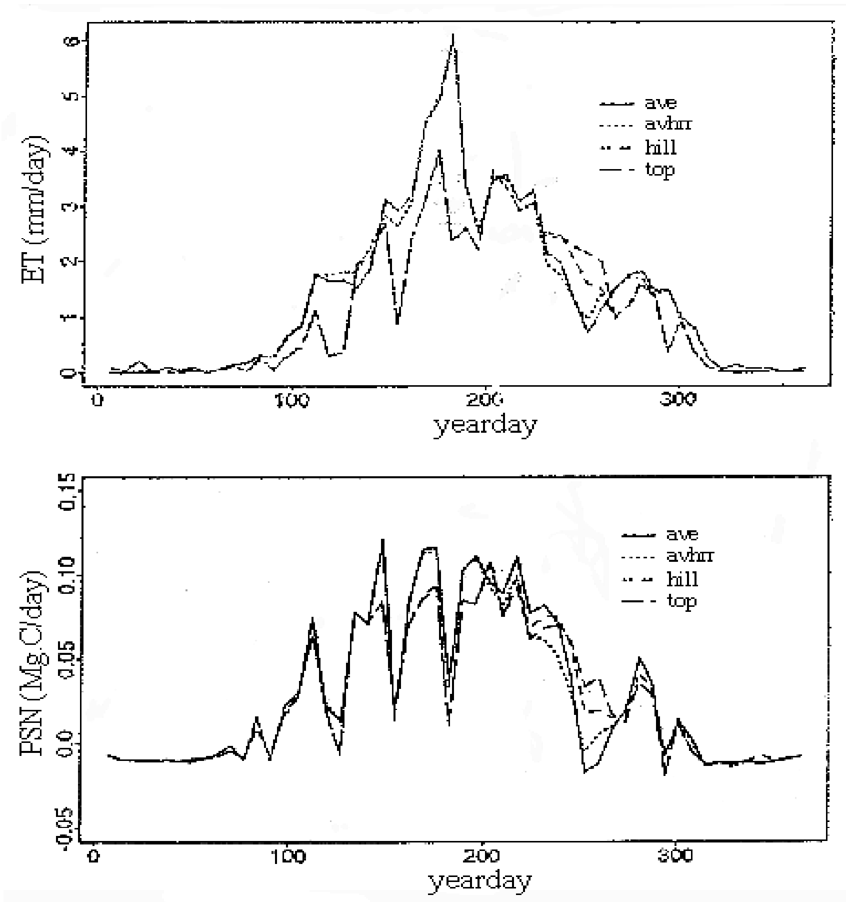

Figure 1.5
Simulation of water and carbon budgets by hydroecological model with a range of surface representations. The legend is defined in the following paragraph.

Simulation of water and carbon budgets (Figure 1.5) were carried out by hydroecological model with a range of surface representations from fully lumped (ave), to locally lumped by hillslopes (hill) or by grids approximating AVHRR footprints (avhrr), to more distributed, resolving hillslope hydrologic redistribution of soil water downslope (top). Evapotranspiration (ET) and net canopy photosynthesis (PSN) show that more lumped approaches (ave and avhrr) tend to show more extreme behavior in the areally average flux rates as the full system either wets up or dries down uniformly, while more distributed approaches show a buffered response to both wetter, more optimal conditions (near yearday 180), and drought conditions (around yearday 250). This reveals potential bias due to lumping. The more distributed approaches made use of both spatial patterns and covariance of critical surface parameters such as leaf area index (LAI), slope, aspect and soil conditions, as well as incorporating the effects of downslope translocation of water down drainage paths.

More lumped approaches tend to show more extreme behavior in the areally average flux rates as the full system either wets up or dries down uniformly, while more distributed approaches show a buffered response to both wetter, more optimal conditions, and drought conditions.

The second example is from a very different region, the Southern Old Black Spruce site of the BOREAS experiment, near Prince Albert, Saskatchewan. This site is very flat lying, with

only a few meters of total relief within about a square kilometer around a flux tower, and a groundwater table close to or intersecting the surface. A variably sparse canopy of black spruce overlies a forest floor largely dominated by feather moss or sphagnum. Sphagnum occurs in wetter sites with a sparser canopy while feather moss occur in somewhat drier sites with more closed canopies. Significantly, sphagnum is capable of drawing substantial water from the groundwater table by capillarity, while feather mosses appear to be largely precipitation irrigated, and therefore shows much greater variability in moisture content over time. Similar to the Soup Creek site, the landscape has a distribution of surface wetness conditions, with areas of greater sphagnum cover maintaining higher water content and surface evaporation and carbon assimilation during dry periods. However, if 1-km block samples were taken with modal filter on surface cover, sphagnum would largely disappear as it makes up no more than 20 to 40 percent of the flux tower site. The results demonstrate that if the area was aggregated with a modal filter, the lack of the sphagnum stratum would bias the results, particularly during dry periods. Therefore, maintenance of at least aspatial distribution functions of surface conditions is required in this case to avoid bias in aggregation.

The common behavior observed in theese simulation experiments due to aggregation is to cause a bias towards underestimating areally averaged surface evapotranspiration and latent heat flux during drydowns.

The final example involves simulations of the full South Platte watershed, with an area of approximately 63,000 km2 in western Nebraska, southern Wyoming and Colorado . Most of the watershed is in the high plains region, while the headwaters are in the Rocky Mountain Front Range. While it may appear obvious to separate these two distinct physiographic and climatic provinces, at the level of resolution of most global atmospheric circulation models, this may be difficult. Figure 1.6 shows simulated areally averaged runoff production over the full basin over the year 1992, with a distribution of model simulation units ranging from one (fully lumped) to over 150 (denoted as simulation 8, or “many”). The figure is essentially the distribution of runoff hydrographs over a range of simulations with varying degrees of model distribution . The significant effect is the threshold response of runoff as the model becomes sufficiently distributed to adequately resolve the Front Range and High Plains as distinct physiographic and climatic units. While this effect may appear to be an obvious expectation, over smaller regions, similar effects can be seen by lumping together regions that are nonstationary in terms of means and covariances of important controlling surface and climate conditions.

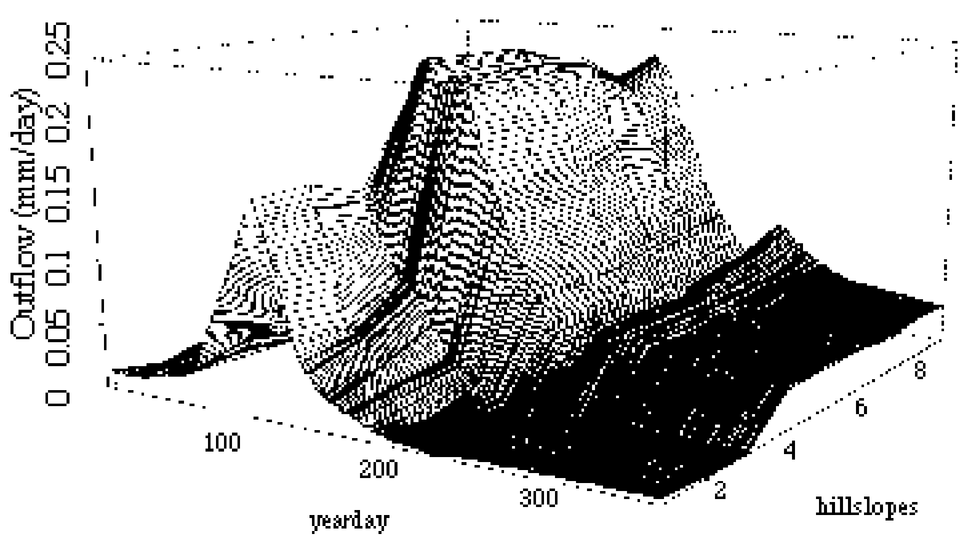

Figure 1.6
Simulated outflow through time and scale for the South Platte basin for the year 1992.

Discussion

The common behavior observed in these simulation experiments due to aggregation is to cause a bias towards underestimating areally averaged surface evapotranspiration and latent heat flux during drydowns. This is partially due to the shape and steepness of soil characteristic curves relative to the distribution function of surface soil moisture, but also reflects interactions and spatial covariance of vegetative cover, soil type, and smaller scale climatic patterns. Neither the distribution function of soil moisture nor the spatially co-varying patterns of surface variables are maintained as surface characteristics are increasingly aggregated. A common limitation in all the examples is that the model approach uses prescribed meteorology rather than a coupled land surface/atmospheric model. Progress is being made in coupling the distributed land surface approach with RAMS (e. g., Walko et al., 1994) in which case the significant feedbacks may be better evaluated. However, it might be speculated that a coupled boundary layer would respond to surface that is biased to be drier by deepening, entraining more upper atmosphere air, and drying further, which, due to the lack of wet surfaces (particularly non-stomatal forest floors), may develop a positive feedback.

In summary, Band's presentation illustrated that detailed physical treatment of 1-d soil hydrology processes may not be sufficient to resolve important feedbacks between surface and atmosphere. This is due to the uncertainty of process representation within the 1-d model conceptualization, difficulty in adequately parameterizing effective average conditions over large land areas, and the inability to resolve the apparent "buffering" capacity of landscapes brought about by lateral redistribution of soil water over longer time scales that maintains more persistent wet areas through drought conditions.

Detailed physical treatment of 1-d soil hydrology processes may not be sufficient to resolve important feedbacks between surface and atmosphere

Acknowledgments: Vapor flux data for the BOREAS Southern Old Black Spruce tower flux site was measured and provided by TE-1, Dr. Paul Jarvis, through the BOREAS Information System.

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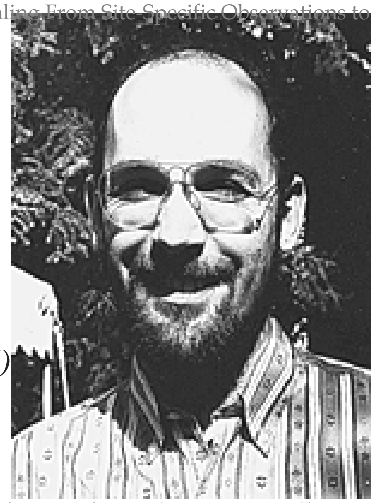
Scaling Issues in Forest Succession Modeling



Harald Bugmann

Potsdam Institute for Climate Impact Research (PIK)
Potsdam, Germany

Observations, experiments and modeling in ecology are often performed at very small scales in time and space, typically covering several weeks to a few years and several square meters to a few hectares, respectively. Many ecologists have noted that ecological knowledge is difficult to scale up in time and space, and therefore one wonders how present-day research results can be applied to alleviating concerns about the future development of the ecosphere. For at least three reasons, scaling is difficult in ecology: firstly, because ecosystems are organized hierarchically, with many feedback processes across scales; secondly, because ecosystems are highly non-linear systems; finally, because ecosystems are spatially heterogeneous ("patchy") as a consequence of spatial variations in (micro-) climatic and edaphic (influenced by soil) properties as well as disturbance regimes. Yet, there are still many instances where research results obtained at small scales are extrapolated linearly to much larger scales. A particularly impressive example for this is a study where the findings from experiments with sour orange trees during one growing season were extrapolated linearly across temporal and spatial scales to address questions relating to the long-term behavior of the global carbon cycle.

Scaling is difficult in ecology because ecosystems are organized hierarchically, they are highly nonlinear systems, and they are spatially heterogeneous.

Bugmann reviewed the state-of-the-art regarding scaling issues in forest gap models, the most widespread class of models used to describe and project the dynamics of forest composition across several centuries (Shugart, 1984). Most emphasis was put on spatial upscaling, but temporal upscaling and downscaling issues were briefly covered as well.

Upscaling

Two different modes of upscaling were distinguished (see Figure 1.7 below). Firstly, implicit upscaling was discussed, i. e. taking scale-dependent features into account while developing model equations so as to formulate the model according to the requirements of its particular scale. Using three examples from forest gap models, Bugmann showed that this way of scaling is quite important, but hasn't always been taken into consideration appropriately.

Secondly, explicit scaling was addressed, i. e. using procedures that typically involve numerical simulations to scale up the response of a local model in space and/or time. Based on the categorization by King (1990), Bugmann provided examples from gap modeling studies using two different extrapolation methods. Specifically, he presented simulation results aimed at recovering the spatial pattern of natural forest vegetation for the federal state of Brandenburg, Germany, which covers almost 30,000 km2. To apply gap models at such large spatial scales is a real challenge - earlier studies typically dealt with applying these models at a couple of individual sites scattered across a landscape. The results from the study showed that spatial extrapolation to such large scales is possible, given that there are no large-scale disturbances such as fires or insect attacks that determine the behavior of the system at the landscape to regional scales. For the case of Brandenburg, this assumption is probably realistic, whereas it

would be wrong in other regions, e. g., in the boreal forest. The optimistic corollary of this is that we appear to be narrowing the spatial gap between climate models and impact models.

Spatial extrapolation to such large scales is possible, given that there are no large-scale disturbances such as fires or insect attacks that determine the behavior of the system at the landscape to regional scales.

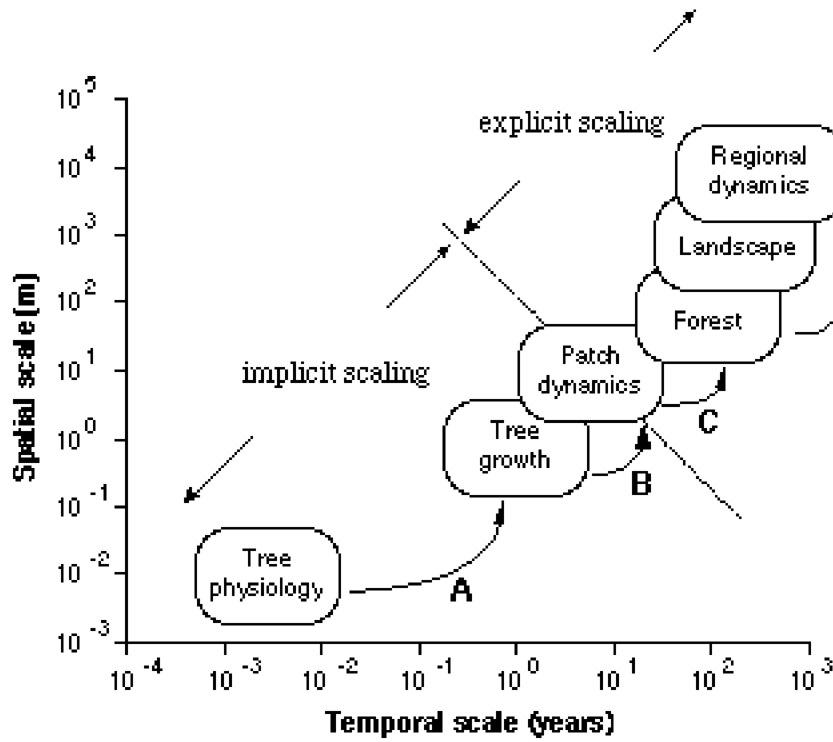


Figure 1.7
Temporal and spatial scales and how they are bridged in forest gap models. In most of these models, tree physiology is not treated explicitly. Instead, the scale transition A is handled by introducing scaled, aggregated response functions ("parameterizations"). The gap dynamics hypothesis (Shugart, 1984) is used to achieve the scale transition B from the tree to the patch. A statistical interpretation of the results from many simulated patches is applied to derive the behavior of an entire forest (Bugmann et al., 1996) (C). Finally, spatially distributed simulation is employed to bridge the gap between an individual forest and forested landscapes/regions (D). A and B are implicit scaling methods, whereas C and D are explicit scaling methods. The figure is adapted from Urban et al. (1987).

Unfortunately, the simple models used in these examples do not and can not provide all the variables that are required for land surface parameterizations, such as albedo and the vegetation-dependent fluxes of latent and sensible heat. On the other hand, the more detailed succession models that provide these variables are much more difficult to upscale to the regional level because they require many input variables at a high temporal resolution, which are quite difficult to provide at the landscape scale. Moreover, simulations with these models at the regional scale would hardly be feasible due to their high computational demand.

Given dynamic models that are based on differential or difference equations, it is tempting to speculate that scaling up in time simply corresponds to numerical integration. Indeed, in cases where the model is not very complex and can be integrated easily over longer periods of time, numerical integration is most often used for temporal upscaling. In the case of gap models, there appears to be no immediate need to employ other methods of temporal upscaling because

the model behavior can rather easily be simulated for several centuries to a few millennia. However, with other kinds of models numerical integration is often impractical. For example, most detailed physiological models can barely be integrated for several hundred years due to computer hardware limitations. Even if this is feasible, integration errors may add up to such an extent that the signal of the model is buried in the noise of the integration.

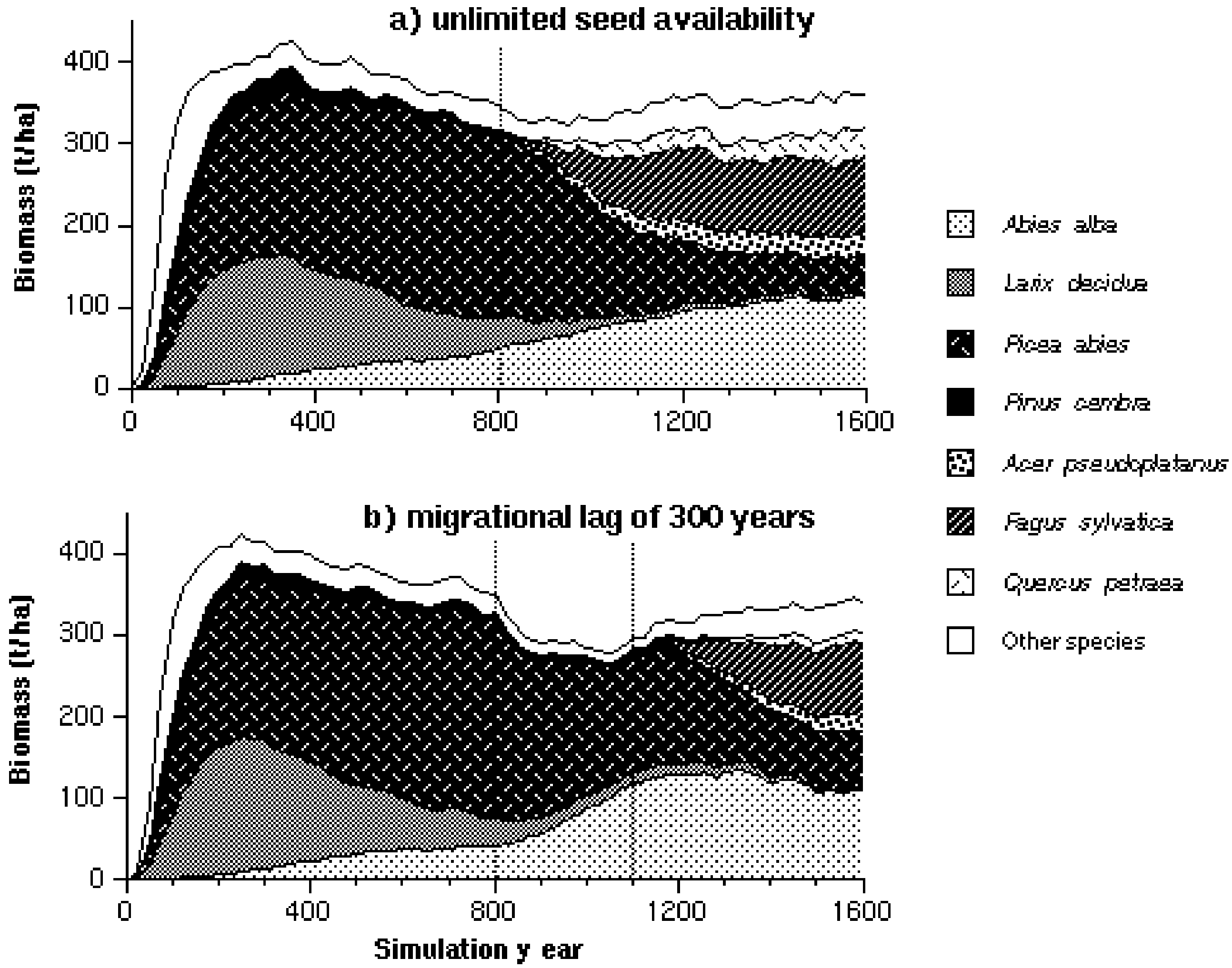


Figure 1.8

Example of a temporal upscaling problem in forest gap models when neglecting migrational lags induced by climatic change. The behavior of the ForClim model is simulated for 800 years under current climate, starting from bare ground, for the site Davos (Switzerland). In year 800, an arbitrary step change of the climate of +3°C is imposed on the model, assuming that the new climate remains constant until the end of the simulation in year 1600. The upper panel shows the model behavior when assuming no migrational lag, as done in most studies published to date. The lower panel is based on the assumption that all the species not present under the current climate require 300 years to migrate naturally to this high-elevation site, which is located in a complex topography with many migrational barriers.

More importantly, in some cases numerical integration may not be appropriate at all due to internal model constraints. For example, with respect to gap models it is typically assumed that seeds of all species are available at any site and at any time; it is only the environmental

conditions that control the exclusion of species from the establishment process. This implies that migrational lags usually are not considered in these models. Hence under scenarios of climatic change, the models may be too optimistic with respect to the availability of new species that could grow if they were there, but in reality will not grow because they require many years to immigrate.

To study the sensitivity of a gap model to the assumption of unlimited versus limited seed availability, a series of simulations along an environmental gradient in central Europe was performed with the ForClim model (Bugmann, 1996). Climate was assumed to change in a step fashion by +3°C in simulation year 800. In one set of simulations, an arbitrary migrational lag of 300 years was introduced, i. e., the species not present under current climate were assumed to be available only after simulation year 1100. This can lead to quite different projections of the species composition and aboveground biomass during several centuries after the climate has changed. For example, at the site Davos (see Figure 1.8 below) the subalpine Larix decidua - Picea abies forest simulated under the current climate is gradually replaced by a montane Abies alba - Fagus sylvatica - P. abies forest by year 1300 if unlimited propagule availability is assumed (Figure 1.8a). Assuming a migrational lag of 300 years (Figure 1.8b) induces a persistence of the subalpine forest after simulation year 800, whose biomass is reduced due to increased reproduction failure of the dominant species, P. abies, and an increase in the abundance of A. alba. When the other species become available in year 1100, the total biomass recovers, and the abundance of A. alba decreases under the competition with deciduous species, most notably F. sylvatica. Under this scenario, the composition of the montane forest reaches an equilibrium only by year 1600 (Figure 1.8b). These simulations corroborate the suggestion of earlier studies (e. g., Solomon, 1997) that it is important to take plant migration into account if we are to reliably assess the transient behavior of the biosphere, e. g., with respect to carbon storage.

Under scenarios of climatic change, the models may be too optimistic with respect to the availability of new species that could grow if they were there, but in reality will not grow because they require many years to immigrate.

Downscaling

Finally, the discussion of downscaling problems showed that the derivation of regionalized scenarios of climate change that are relevant at the spatial scale of forest gap models is an indispensable prerequisite for realistic impact assessments with these models in many geographical areas (Bugmann, 1997). Based on the application of the ForClim model, Bugmann concludes that at least some forests appear to be quite sensitive to the magnitude of projected climatic changes, and simply using grid-cell average anomalies from GCS simulations is most likely inappropriate to drive ecosystem models.

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At least some forests appear to be quite sensitive to the magnitude of projected climatic changes, and simply using grid-cell average anomalies from GCS simulations is most likely inappropriate to drive ecosystem models.

Estimating Sub-Grid Scale Processes Using Oceanographic Data

William A. Gough

University of Toronto at Scarborough
Ontario, Canada

Upscaling of site-specific measurements is a case where our perceptions of what processes are taking place may influence the use of the data.

Gough discussed oceanic measurements and their current and potential uses for coarse resolution ocean and climate modeling. He reviewed ocean measurements and climatologies, discussed how these measurements are used, and then focused on the use of inverse methods to estimate the oceanic flow field and mixing coefficients that are of potential use to modelers. He then assessed the efficacy of such approaches and the complicating problems of the ocean data. The following questions were examined: What comprises ocean data? How is it currently used? What are inverse methods? Can large scale mixing coefficients be estimated by inverse methods? Where do we go from here?

What comprises ocean data?

Humankind has a long history of observing the sea. Traditionally, temperature and salinity dominate the recorded observations, although in more recent years these data have been complemented by an increasing array of geo- and biochemical tracers such as dissolved oxygen, tritium, nitrates, phosphates, and CFCs. Direct current measurements have also been made. In the last decade, satellite technology has greatly enhanced our ability to assess the ocean surface. There are, however, strong biases in the ocean data set, i. e., for practical reasons there are many more surface observations than measurements of the deep ocean. The North Atlantic Ocean is relatively data rich compared to other parts of the world ocean.

The nature of the ocean data set in some respects has lead to a specific oceanographic culture or paradigm. Traditional views of ocean circulation in many ways may still haunt our current approach to collecting and using ocean data. Upscaling of site-specific measurements is a case where our perceptions of what processes are taking place may influence the use of the data.

How are ocean data used?

The question that has faced oceanographers is how to use this spatially and temporally incoherent data which is neither synoptic (snapshot at one time) nor truly climatological. With the heavy weighting of surface data, the question has been refined to: How much can be inferred about the ocean circulation, both surface and deep, from surface observations?

Two distinct camps have evolved to try to answer this question. The first is composed of prognostic modelers who have developed models of the ocean circulation based on the fundamental physics of fluid flow. Oceanic data are used by this group in two ways, estimating (parameterizing subgrid scale processes using data to tune the model) and for validating the model.

The other camp uses ocean data to infer what is occurring in the ocean. Olbers (1989) quotes Fofonoff, "Given the answer, what was the question?" This has been the traditional approach in descriptive oceanography. Following temperature and salinity distributions has lead to the characterization of water masses in the oceans, an extremely useful representation of the world ocean circulation, although potentially misleading (Wunsch, 1996). The view that the world ocean is a simple, large scale flow prevails, often in subtle ways, in much of oceanic thought. However, the MODE experiment of the 1970s and current meter measurements showed the presence of mesoscale eddies (tens of km scale) which locally swamp the large scale signal in the measurements. This approach has evolved rapidly in the last twenty years through the use of powerful mathematical tools usually referred to as inverse methods. These tools, discussed below, use hydrographic (temperature and salinity) and tracer data to calculate velocity fields and in some cases mixing coefficients.

What are inverse methods?

Mesoscale eddies (tens of km scale) locally swamp the large scale signal in the measurements.

As defined above, inverse methods seek to determine characteristics of the ocean flow from the available data. To do this, a theoretical framework that can be exploited needs to be developed. In essence, given that we have some oceanographic measurements, we can backtrack and deduce the oceanic dynamics (flow and diffusion) necessary to produce the measured distribution of ocean properties such as temperature, salinity and other tracers. Refer to Wunsch (1996) for details on this methodology.

Can large scale mixing coefficients be determined from inverse methods?

Smaller scale processes, such as mesoscale eddies, are modeled as diffusive processes. This modeling is referred to as parameterization, the representation of subgrid scale processes using resolvable model variables. In this instance, the mesoscale eddies are assumed to behave diffusively. This is a presumption of an emergent property. Holloway (1989) says that this parameterization lacks, "... systematic derivation from some averaging procedure over sub grid scale motion,"but that it is "... understandable at an intuitive level and is relatively straightforward to implement into models."

There is a high degree of anisotropy with oceanic diffusion; horizontal diffusion is typically represented as seven orders of magnitude larger than vertical diffusion. It has been found that ocean models are highly sensitive to the magnitude of diffusion constants. Bryan (1987) found that the strength of meridional flow depended strongly on the value chosen for vertical diffusivity.

A further subtlety is introduced by considering that mixing occurs predominantly along isopycnals (surfaces of constant density) rather than horizontally. It is therefore of interest to obtain estimates of mixing coefficients from observations and to investigate if mixing preferentially occurs along isopycnals in this data.

Obtaining mixing coefficients from observations

Mixing coefficients have been estimated using inverse methods in a number of studies using both climatological and "synoptic" data for both large and regional scale circulations. The results have been mixed and raise a number of issues about this approach and the data used. Olbers et al. (1985) and Olbers and Wenzel (1989) examined climatological data in the

North Atlantic and Southern Ocean respectively. Mixing is explicitly represented in the tracer conservation equation along and across isopycnals. The Levitus (1982) data set is used for the North Atlantic analysis. Using inverse methods flow velocities and mixing coefficients are estimated. The surface flow produced in this work appears quite reasonable. Values for the isopycnal mixing coefficient vary from 1.0 to 3.0 x 103 m2/s for the upper 800 m of the ocean and 0 - 10.0 x 102 m2/s for the deeper ocean. These estimates are similar to that typically used in ocean general circulation models (103 m2/s). The diapycnal diffusivities ranged from 0 - 3.0 m -4/s in the upper ocean and 0 - 1.0 m-4/s in the deep ocean. Peak values for both diffusivities occurred in Gulf Stream and North Atlantic Drift regions.

Olbers et al. (1985) called into question the suitability of using the Levitus data set for this type of calculation and its impact on his results. The temperature and salinity data were collected from hydrographic stations and bathythermograph surveys. The data was averaged and gridded onto 1° square resolution. This is a smoothing, filtering, and interpolating process that aims to reduce data noise arising from both measurement and unresolvable processes. If this is not done there is the potential of aliasing high frequency oscillations into lower frequencies. In this process the upscaling of site specific measurements has been done by eliminating the variability. This resulted in the western boundary flow (Gulf Stream) being less intense than expected. They also assert that much of the diffusive structure implied in the isopycnal and diapycnal coefficients may be due to the climatological averaging.

It has been found that ocean models are highly sensitive to the magnitude of diffusion constants.

In Olbers and Wenzel (1989) the Southern Ocean was examined using a different climatological data set. Mixing coefficients (along with reference velocities) were calculated. The mixing parameterization was tested in two ways by orienting the anisotropic mixing first, isopycnally, and then, horizontally. In this way, isopycnal and diapycnal mixing coefficients and vertical and lateral coefficients can be compared. It was found that there was not a significant difference between the two parameterizations. In a zonal average diapycnal diffusivity ranged from 3.0 x 10 -5 m2/s to 3.0 x 10-4 m2/s for the upper ocean and an order of magnitude larger for the deeper ocean. Spatially the peak value is coincident with the strong Antarctic Circumpolar Current, a result consistent with the North Atlantic analysis. The isopycnal diffusivity ranges from 102 m2/s to 103 m2/s for the upper ocean with a reduction by a factor of two for the deeper ocean levels. Once again the peak value tended to coincide with the Antarctic Circumpolar Current. As before, diapycnal/vertical diffusivity values fall within the range of values currently used in ocean modeling. However, the vertical structure of diapycnal diffusivity is different for the two locations, decreasing with depth in the North Atlantic and increasing with depth in the Southern Ocean. It is possible that the increasing diffusivity for the Southern Ocean is a result of periodic convection which would tend to result in an increase in diapycnal diffusivity.

Because of the reputed inconsistencies in the original Levitus data and its gridding procedure (Wunsch, 1996), it is of interest to examine the calculation of mixing coefficients using a temporally and spatially coherent data set. This had been attempted by several researchers. Tziperman (1988) concluded that the inverse model could not fully resolve the mixing coefficients, i. e., they were not significantly different from zero and were not needed to produce a reasonable inverse.

Where do we go from here?

The upscaling of site specific oceanographic data has been reviewed. Specifically the focus was on obtaining mixing coefficients from existing oceanographic data sets suitable for use

in coarse resolution models. Usable coefficients have been obtained by employing methods on climatological data. This was based on the presumption of an emergent property when upscaling, i. e., that sub-grid scale processes acted diffusively. This is further hampered by the necessary use of smoothing, filtering and interpolating in order to produce an apparently cohesive climatology of ocean observations. How useful or meaningful are the coefficients generated? Are they an artifact of a presumptive emergent property or massaged data and perhaps are overestimates as suggested by Wunsch (1996)?

There is also the possibility that oceanographic community has fallen into a tautological pitfall. Olbers et al. (1985) used the Levitus data set. This data set is also commonly used by ocean general circulation modelers. In the model development, tunable parameters, such as the mixing coefficients, are adjusted to achieve a “reasonable” flow as measured by the overturning strength, thermocline depth, and bottom temperature. Is it surprising that the inverse of the Levitus data set, which uses a simple conceptual framework for the ocean physics, produces mixing coefficients similar to those that are used in the models? In some respects both groups may have fallen victim to the traditional view of smooth oceanic flow.

Tunable parameters, such as the mixing coefficients, are adjusted to achieve a “reasonable” flow as measured by the overturning strength, thermocline depth, and bottom temperature

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A Scale-Related Difficulty in Switching from Fossil Fuels to Renewables: Renewables are Highly Land Intensive

Christopher Green

McGill University
Montreal, Quebec, Canada

Conversion from fossil fuels to renewable energy sources poses a potentially serious scale-related problem: in their current form, renewables are very land intensive.

The increase in economic progress in the last two centuries owes much to our ability to harness energy. Most energy is produced by fossil fuels - long-stored solar energy. Although renewables such as hydropower, wind, biomass and solar thermal contribute at the margin to the world's energy supply, currently, they are no substitute for fossil fuels for meeting baseload energy needs. One reason for this, Green argues, is that renewables are highly land intensive. Heavy reliance on renewables would increase competition for land, much of which has good alternative uses. Since the desire of an increasing world population for improved economic well-being inevitably means increased energy use, albeit greater energy efficiency will slow the rate of increase in energy consumed, it is predictable that most of the increase will have to be met by fossil fuels in the foreseeable future.

Therein lies a problem. Fossil fuel use causes the emission of greenhouse gases (GHGs), the most important of which is carbon dioxide (CO_2). There is mounting evidence to support the prediction that GHG emissions from a continued high level of fossil fuel use will eventually raise the earth's average temperature. A rise in global average temperature implies a change in global climate, with less predictable effects on local climate and weather, and in turn, on local economic activity, health and social structure.

Scaling Up of Renewable Energy Sources: The Land Intensity Problem

Conversion from fossil fuels to renewable energy sources poses a potentially serious scale-related problem. Fundamentally, the problem involves a little understood facet of renewable energy technologies: in their current form, they are all very land intensive with the obvious exceptions of geothermal, ocean thermal and tidal energy. Thus, what may be technically and economically feasible on a small scale may not be so on a large, global scale, either because there may be insufficient land with the appropriate characteristics or there are better (more valuable) uses of land.

In order to get some idea of the problem posed by large scale use of renewable energy technologies, it is useful to establish some benchmarks. These are set out below in Tables 1.9 and 1.10. Table 1.9 indicates the number of Quads or exajoules (EJ) of energy produced globally in 1988 and 1996, and the least that is likely to be needed in 2100. Table 1.10 indicates what it currently takes to produce one Quad (=1.055 EJ) of energy per year.

World Energy Production

Year	Quads (1015 BTU)	Exajoules (EJ) (1018 Joules)
1988	320[a]	338
1996	359 [a]	379
2100 (LESS estimate) b	682	720

Table 1.9 (above)
1 Quad = 1.055 EJ
Sources:
a U. S. Department of Energy. (1990) National Energy Strategy, Interim Report. Washington, D. C., April 1990;
b IPCC (1995) WG II Ch. 19, Part I, B.)

Physical-Technical Hurdles to Displacement of Fossil Fuels to Produce One Quad (1015 BTU) of Energy at Point of Use [a]

Fossil Fuel:	Three 150,000 barrel a day oil refineries operating 365 days a year
Hydroelectricity:	All U.S. hydroelectricity delivered to point of use = 0.95 Quads b. Only 0.5 Quads remain to be developed
Biomass:	Short rotation tree crops, 7,800 to 18,750 square miles (20,202 to 48,563 km2)
Methanol:	20,000 to 50,000 sq. miles of trees (51,800 to 129,500 km2)
Ethanol:	13,000 sq. miles (33,670 km2) of arable land in a climate suitable to sugar cane c
Wind:	2,675,000 wind turbines of 500 kW capacity centered in 12 Great Plains and western states
Solar:	(at 15% solar cell efficiency) a) Tucson, Arizona: 541 sq. miles (1,401 km2) of photovoltaic collector cells, inside a 1,147 sq. mile (2,971 km2) area b) Seattle/Duluth: ~1,700 sq. miles (4,403 km2) inside a 3,640 sq. miles (9,428 km2) area
Solar-Hydrogen:	In addition to land, 57.4 million gallons (217.3 million liters) of water per day is needed, or enough to supply a city of 500,000 people
Nuclear Fission:	1.8 Quads of electricity delivered in 1988. Each additional Quad requires 53 1,000 MW generating stations

Table 1.10 (above)

[a] U. S. consumed 80.8 Quads in 1988 according to U. S. Department of Energy, National Energy Strategy, Interim Report, April 1990
[b] At 0.40 actual capacity factor
[c] Total U. S. cropland is approximately 600,000 sq. miles (1,554,000 km2)

Source: H. Douglas Lightfoot and C. Green (1992). The Dominance of Fossil Fuels: Technical and Resource Limitations to Alternative Energy Sources. McGill University, Center for Climate and Global Change Research (C2GCR). Working Paper 92-6, May.

What may be technically and economically feasible on a small scale may not be so on a global scale, either because there may be insufficient land with the appropriate characteristics or there are more valuable uses for the land.

It is clear from Table 1.10 that, with the exception of nuclear power, all of the non-fossil fuel energy alternatives are very land using. Essentially it takes many thousands of square miles to produce a Quad (or EJ) of energy from biomass or other vegetation-related energy sources. For solar energy, it takes anywhere from 1,000 to 3,000 sq. miles (2,590 to 7,770 km2) to produce a Quad of energy, the specific amount depending on locale. In the case of wind energy, it takes 4,200 square miles (10,878 km2) in a windy locale to produce a Quad of energy with one turbine per acre (2.5 turbines per ha). If the turbines can be packed more densely (say 2 per acre), it takes an area of 2,100 square miles (5,439 km 2) covered with turbines to generate a Quad of energy.

Hydropower is also land intensive. For example, it is estimated that a huge expanse of Northern Quebec would be inundated if Hydro-Quebec were to build all three phases (only Phase I now exists) of the planned James Bay project; yet delivered energy from all three phases would be less than a Quad. Not only are each of the renewables land intensive, but they are site-specific as well. Only some land, especially in the tropics, but in some mid-latitude sites as well, is appropriate for fast growing plantation biomass that requires substantial water as well as sun and warm temperatures. Few locales have sufficient insolation and suitable terrain with enough water to make large scale solar power operations feasible. Even then there is a storage problem. The same is true of wind energy, which is typically most abundant in locales far from centers with a large demand for energy.

The technical feasibility and economic competitiveness of a renewable technology is a necessary but not sufficient condition for its application as a baseload alternative to fossil fuels at a global level.

The message of the preceding paragraphs is that the technical feasibility and economic competitiveness of a renewable technology is a necessary but not sufficient condition for its application as a baseload alternative to fossil fuels at a global level. If renewables are to be treated as worldwide substitutes for fossil fuels, it is also necessary to consider their land (area) and site requirements. To Green's knowledge, this has not been done on a systematic basis for any renewable, with the possible exception of biomass, which is considered below. Thus, alternative energy scenarios discussed by the Intergovernmental Panel on Climate Change (IPCC 1995, Working Group II, Chapter 19) such as FFES (Fossil Free Energy Scenario) and LESS (Low -Emissions Supply System) may be prone to a scaling problem. Land constraints may stand in the way of heavy reliance on renewables in a low carbon emission world. The example of biomass is illustrative.

The IPCC (1995) Working Group II, in its chapter 19, "Energy Supply Mitigation Options," gives extensive attention to low CO2-emitting energy supply systems - ones that ostensibly could replace fossil fuels by the end of the next century. Various versions of a Low-Emissions Supply System (LESS) were constructed, one emphasizing the role of biomass, another nuclear, another natural gas. The estimated energy use under these scenarios is in the range of 600-700 EJ in the year 2100 (IPCC 1995, II, 19-8:624). In each of the IPCC scenarios, fossil fuel use declines and biomass increases significantly over the next century.

It is useful to probe the land requirements for biomass under the LESS constructions. The IPCC provides estimates of the number of hectares covered by biomass energy plantations, by region, under the alternative LESS constructions (IPCC 1996, II, 19 -11:627). The estimates imply that major sections of Africa, South America and Australia would need to be planted in biomass in each of the scenarios. In the biomass-intensive scenario, by the year 2100, 572 million hectares would be planted in biomass globally or 2.2 million sq. miles (5.7 million km2). Assuming the required amount of land is still available, and it is economically sensible to convert it to biomass plantation, the LESS construction suggests that the world could be largely weaned from its dependence on fossil fuels.

The large substitution away from fossil fuels in a biomass-intensive world would, in principle, allow for a large reduction in CO2 emissions (IPCC 1995, II, 19-13: 629). It is estimated that world production of energy in 2100 will total around 720 EJ (almost double the present 380 EJ). According to the LESS estimates, the conversion to biomass and other renewables would result in annual CO2 emissions falling to 1.78 GtC per year (by 2100) compared to the 6.5 GtC emitted in 1990. The resultant 70 percent decline in emissions from current levels (and more than 90 percent from a business-as-usual baseline) would be sufficient to stabilize the atmospheric concentrations of carbon dioxide. In the LESS scenario, the major factor in the decline in CO2 emissions is the production of 325 EJ from biomass. The 325 EJ are produced from 572 million hectares of plantation biomass. Another 250 EJ would be produced from "intermittent" renewables (solar, wind) and solar hydrogen. But as shown earlier, all of these, too, are land intensive.

The LESS biomass-intensive construction is a rosy scenario, and taken at face values seems so simple it doesn't even require any major technological advance. In fact, it seems to solve the energy-climate change problem by turning back the clock. But it is too simple. In an increasingly populated world, LESS requires enormous amounts of land to be devoted just to energy production. Even assuming there is sufficient land, along with the soil water and temperature to produce rapid growth vegetation convertible to biomass energy, converting to biomass may not be economically sensible . Land with the qualities just described has an opportunity cost in the form of good alternative uses. One measure of available land for plantation biomass is the estimate of cropland in the recent study of the value of the world's ecosystem services and natural capital (Costanza et al., 1997). There, it is estimated that the world's cropland is 1.4 billion hectares. The LESS biomass-intensive scenario would devote 572 million hectares (or 41 percent of cropland) to biomass production. This is a significant shift of cultivable land resources from food to fuel. It implies important opportunity costs when biomass is promoted on a global scale.

Even assuming there is sufficient land, along with the soil water and temperature to produce rapid growth vegetation convertible to biomass energy, converting to biomass may not be economically sensible.

In sum, what may appear as technically and economically feasible at a micro, or local, level may not be economically sensible when scaled up to a macro, or global, level. Converting from fossil fuels to renewables implies devoting large amounts of land to energy production. But land has alternative uses, the more so in an increasingly populated world. These alternative uses will compete with energy production and the former may turn out to be more highly valued than the latter. In any event, the widespread conversion of land, even if it is possible, will increase the price of land. These possibilities do not, however, seem to be recognized in the literature on a "renewables future." Yet, the issue of alternative uses of land is crucial to how we should think about disconnecting the climate from our overwhelming need to use energy.

Conclusions

The threat of greenhouse warming and global climate change will produce increasing calls for reductions in fossil fuel energy use. A growing world population bent on increasing economic and social well being will require increased energy supplies. Although there is a widespread belief that the potential conflict between environment and energy can be resolved by progressive conversion to renewables, the land-intensity of renewables stands as an important barrier to large scale conversion. Perhaps it is time to look in an altogether different direction - to the development of new non-fossil fuel energy technologies that are not heavily dependent on relatively fixed or scarce factors such as land.

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Perhaps it is time to look to the development of new non-fossil fuel energy technologies that are not heavily dependent on relatively fixed or scarce factors such as land.

Scaling and Demographic Issues in Global Change Research: The Great Plains, 1880-1990

Myron P. Gutmann

University of Texas at Austin
Austin, Texas

Gutmann discussed ways of looking at questions regarding the correct scale at which to study the relationship between population and environment with the goal of demonstrating some appropriate strategies for understanding scaling in studies of population and environment. This research is part of an interdisciplinary project directed at examining the relationships between population, land use, and the environment on the Great Plains. The basic unit of analysis in this work is the county. In addition, Gutmann and colleagues are also gathering data at other scales. For a small number of recent demographic variables, they have data for census tracts, a much finer resolution than the county because the average census tract has a population of about 6,000 persons. Census tract data are readily available in digital format only for 1980 and 1990. They are also interviewing about 150 farm families in the Great Plains, and doing very detailed historical research about a number of communities.

Environment does not always shape population, nor do changes in the population always shape changes in the environment.

The relationship between population and environment is being analyzed in a way that characterizes both population and environment as independent and dependent variables. The fundamental analytic premise is that neither population nor environment is always the driving force. Environment does not always shape population, nor do changes in the population always shape changes in the environment. In this sense, population and environment demonstrate a kind of causal recursiveness, where change in the first produces change in the second in one time period, but those changes later produce new changes in the former.

Major environmental episodes, such as the drought and the Dust Bowl of the 1930s, demonstrate the recursiveness the researchers believe existed. A stylized pattern of recursive causality that may have existed is shown below in Figure 1.11, which links the major environmental episodes that might be found in the standard history of the Great Plains.

The Great Plains have been occupied and exploited by humans for more than 10,000 years. Europeans entered the Plains in the sixteenth century, but they had little or no impact until the end of the seventeenth century. In the twenty-five years following 1850, Anglo and Indian hunters devastated the bison and the U. S. government confined all Indians in the Great Plains to reservations.

In the second half of the nineteenth century, American stock raisers found a region that was lush, a consequence of high rainfall and the elimination of bison and Indian horses, competitors for grass. The late nineteenth century brought new systems of agriculture to the Plains. Good rainfall and a boom in grain prices caused by World War I led farmers to prosper from roughly 1912 to 1920. Grain boom profits led farmers to plow up native grasses and leave the land vulnerable to wind and drought.

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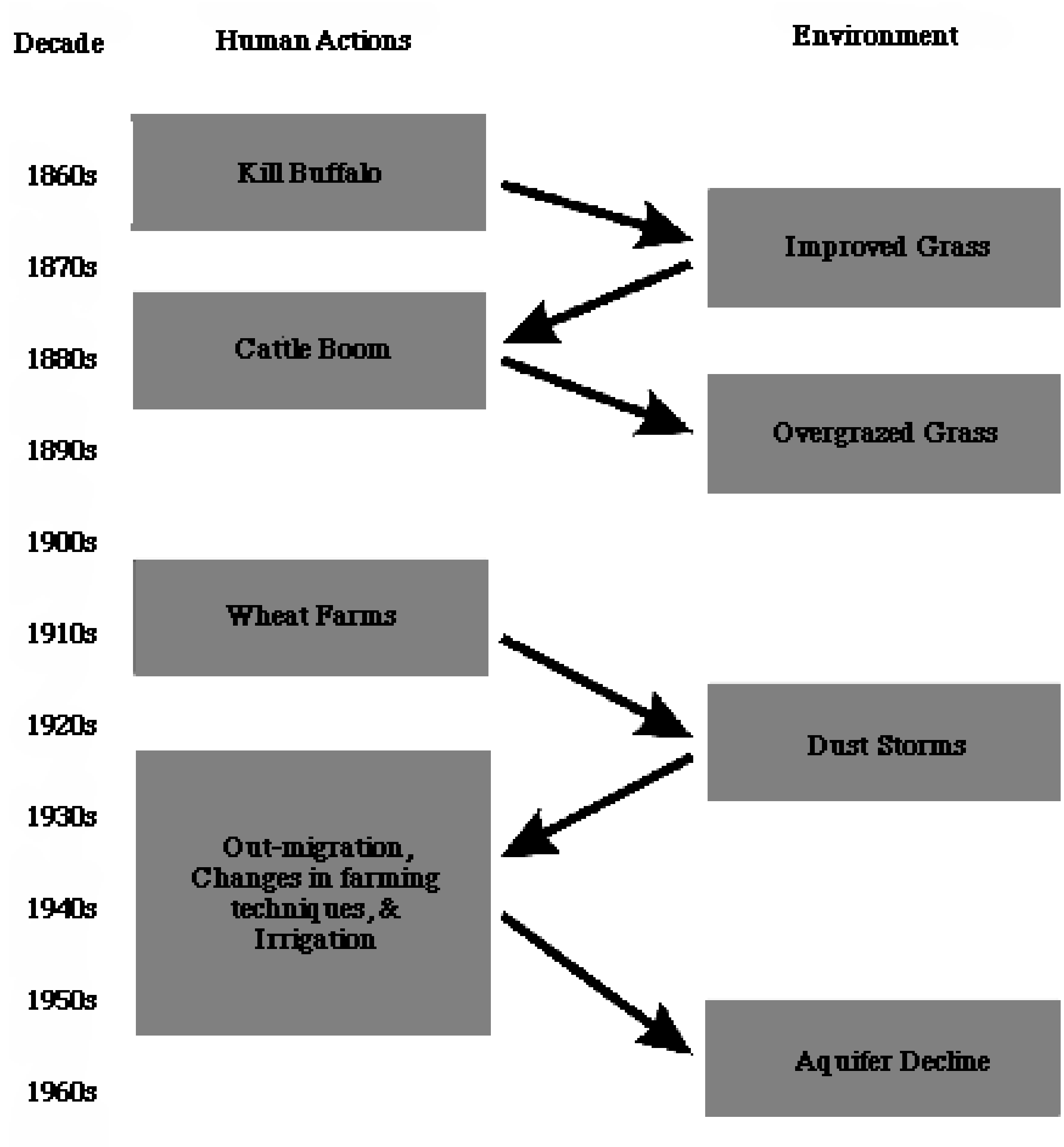


Figure 1.11
A stylized representation of how Great Plains history is recursive

The grain boom ended in the mid-1920s. It was followed by a long drought that lasted from 1932 to 1941 on the Southern Plains, and from 1928 to 1936 on the Northern Plains. The drought brought dust storms and economic collapse, leaving families with failed crops, dead cattle, and eroded soil to desert their farms. The drought also led to massive Federal government efforts to change the environment, society and economy.

In the conventional story-telling of the development of the Great Plains, the plow-up of the grasslands for wheat, combined with the drought of the 1930s, provoked the disastrous dust storms and social dislocation of that time period. While all might not agree that those were the only causes, or that the greatest areas of wheat farming suffered the worst drought and dust storms, there was a causal relationship. Plowed land is a much greater source of blowing dust than uncultivated grassland. Humans responded to the problems of the 1930s. Some migrated

out of the region, although the 1930s were not the period of the greatest out-migration from the agricultural areas of the Great Plains (the 1950s were). Those who remained changed their farming techniques between the 1930s and 1970s.

Scales of Analysis

The data used in this project came at a variety of scales, and these have a strong influence on the research. Demographic data constitute the primary source for much of the analysis. While there are many kinds of demographic data available, population census data constitute the most important source in this work. The U. S. population census data are published at higher levels of aggregation than the individual, such as the city, county, metropolitan area, or state. The smallest levels of aggregation for which there are published data for recent censuses are the block, block group, or census tract. (Census blocks are small areas bounded on all sides by visible features such as roads, streams and railroad tracks, and by invisible boundaries such as city, township, and county limits, property lines, and short, imaginary extensions of streets. A block group is a cluster of blocks having the same first digit of their three-digit identifying numbers within a census tract. Census tracts are small, relatively permanent statistical subdivisions of a county and are delineated for all metropolitan areas and other densely populated counties.) There are few data at levels smaller than the county before 1940.

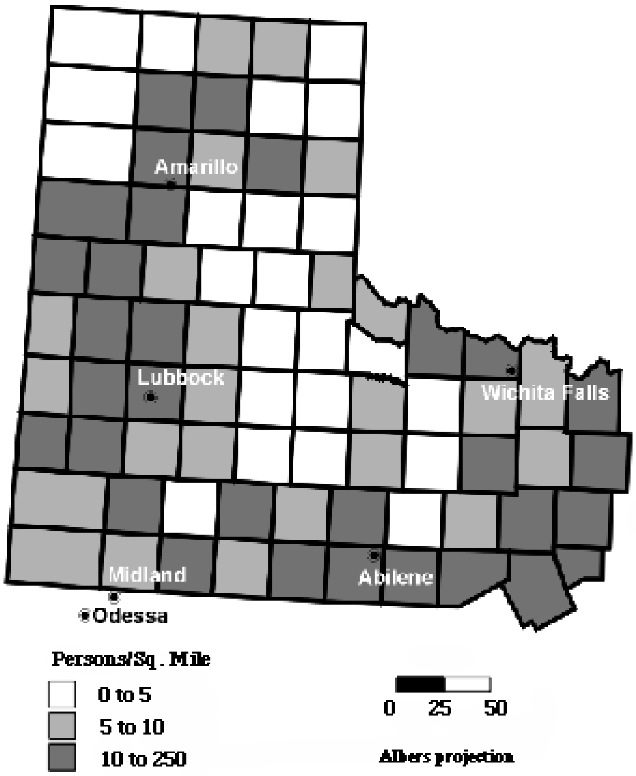
Individual-level data are available for many censuses, but these data are in the form of public use samples, stripped of most characteristics that might permit a person to be identified. In 1990, for example, the smallest identified geographic unit must have 100,000 persons, many more than a single rural county. It is impossible to link these population data effectively to environmental or land use data.

The variety of scales at which demographic data are available leads to the question: what is the appropriate scale at which to conduct the analysis? Figure 1.12 presents data about population density in the Great Plains counties located in Texas. Figure 1.13 presents population density in those same counties, but this time, divided into census tracts instead. Dividing the region into census tracts shows that the rural population is much less dense than it appears at the scale of the county, while the population living in towns is more dense. If one were analyzing the role of human population density on levels of air or water pollution, looking at census tract densities would be much more productive than looking at county densities.

The variety of scales at which demographic data are available leads to the question: what is the appropriate scale at which to conduct the analysis?

Census Land Use Data constitute the second major source of data for this project. The U. S. has undertaken a census of agriculture at regular intervals since 1850. These censuses of agriculture were performed every ten years from 1850 until 1920, and generally every five years since then. Data at the level of the individual farm are scant for censuses taken after 1880. The Census Bureau has always published these data at the level of the county and state, and more recently at the level of the zip code. The publications are extremely rich. In recent years, the published tables (and their digital analogs) include thousands of cells of data for each county. Users need to face the trade-off between rich detail in the number of variables reported and the lack of detail in terms of identifying land use and farm activity in an area smaller than a county.

Other data at different scales are also used in the study. These include soils data (varying polygons), and weather data (weather stations are points). The researchers also get greater detail from the two kinds of small-scale research they are doing. These parts of the research project involve interviews with farm families, plus detailed historical research. In the future, remotely sensed data, either satellite imagery or aerial photographs may be added to the study as well.



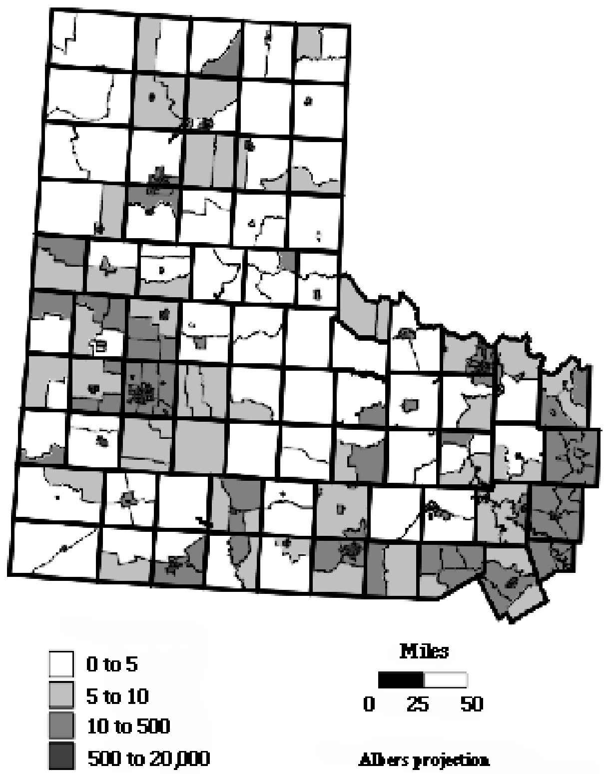


Figure 1.12 (above)
Population Density on the Texas Plains, 1990
(counties as unit of analysis)

Figure 1.13 (above)
Population Density on the Texas Plains, 1990
(census tracts as unit of analysis)

Advantages and Disadvantages of Different Scales

The major advantage of working at a small scale is that environmental conditions and environmental change are geographically precise, and should be measured that way. That task is difficult because most demographic data are not available at this resolution, especially for the past. The same holds for agricultural data. One can, of course, disaggregate, taking smaller areas than counties and assigning the characteristics of counties to them. Such a strategy, while environmentally detailed, risks a false sense of precision, in both description and statistical analysis.

The advantage of working at a large scale, such as counties, is that virtually all data can be converted to that level of analysis. There is no false sense of precision. The disadvantage of working at the county scale is that there is a considerable loss of accuracy if one assumes that the characteristics of a unit the size of a county apply to all its components. This error might lead one to conclude from this analysis that what happens at a unit the size of a county also happens to each of the individual persons, families, and towns within its administrative borders.

Large scales of analysis, such as the county units used in this study, are appropriate to the extent that they are homogeneous. If they are not homogeneous, then it is necessary to consider whether by aggregating smaller units one loses precision or introduces distortions. Looked

at the other way, small units are attractive only so long as they capture the diversity of the environment or the diversity of the human population, and if the data really exist to support them.

Migration Analysis: An Example

Many descriptions of the demographic consequences of climate and environment in the Great Plains discuss the role played by migration as a mechanism for adjustment. The often-told story of the drought of the 1930s emphasizes migration. This history stresses the fact that residents of the driest parts of the Great Plains left the region to go elsewhere when their efforts at farming failed. In a recent paper, Gutmann and colleagues have attempted to test the hypothesis that weather played an important role in determining which counties had the greatest net migration away from the region in the decades from 1930 to 1990. Because the demographic and economic variables are available only at the county level, they perform their analysis at that level.

The major advantage of working at a small scale is that environmental conditions and environmental change are geographically precise, and should be measured that way.

The general findings of the research are as follows: the most important determinants of migration are the extent to which the county has an agricultural economy, and the extent to which there are meaningful alternatives to agricultural employment within the county. Thus, counties with a large proportion employed in agriculture had relatively large out-migration, while counties with a large proportion having a college education had relatively large in-migration. The environmental variables are not always significant, but two groups of those variables are nonetheless worth summarizing. First, counties with relatively greater drought in the 1930s did have more net out-migration than counties with less drought. Second, counties with relatively high elevations had relatively high in-migration during the 1960s and 1970s, during the first phase of the development of a mountain recreation economy in the western Great Plains.

This analysis of the determinants of county net migration works because net migration can only be measured at a large level of aggregation. There are no individual "net migrants," only the record of the counties that migrants have entered and left. There are still perils in this strategy. The environmental variables may be aggregated to a level that may not be homogeneous. Even the demographic units can be a concern. If the urban status of the county is important, care must be taken in cases where the urban area is only part of the county.

Even if the analysis of the impact of economy, society, and environment on migration in the Great Plains at the level of the county is successful, one must also ask if it can be scaled up to larger units, and whether it can be scaled down to the level of individuals, families, and communities. On the scaling down side, the analysis is not yet complete. Nevertheless, the analysis of net migration at the county level appears to reflect the same conclusions as the preliminary research into the experiences of individuals and families.

Scaling up from the county to larger units of analysis poses a number of problems. Could the analysis of county net migration be scaled up to much larger aggregations of county-sized units than the Great Plains region, such as the United States, the North American Continent, or the globe? In other words, can county-level net migration be predicted for areas larger than the Great Plains? The answer appears to be yes, at least for the United States, and perhaps for all of North America.

The success of regional and national analyses of county net migration in response to a stable or changing environment does not necessarily mean that these results can be used to estimate conditions elsewhere in the world or in other time periods. Human responses to drought varied by time period and may have varied by land use. Drought produced out-migration in the 1930s, but it did not produce out-migration in other time periods. Rather, the out-migration from the counties of the Great Plains in the 1940s, 1950s, and 1960s was largely independent of differences in weather conditions, and more likely the result of forces pulling the people of the Great Plains to the growing industrial cities of the Midwest and California. If we attempt to project these findings forward for the United States, or more problematically for the whole world, it can only work if one is imaginative enough to foresee economic and social trends.

The migration results of this study indicate that it is difficult, but perhaps not impossible, to jump from one scale to another in work about population and environment . The key is the ability to predict the complex behavior of humans in the future. Gutmann and colleagues have learned that there are scientifically measurable relationships between environment and human migratory behavior. That is important on its own. They have also learned that humans do not respond to the same environmental change or condition in the same way under all conditions or at all times, even in a single semi-arid region such as the Great Plains. This means that we cannot yet predict how this or any other population will react to similar changes in the future. What we can do now is describe some of the limits on how humans will react, and continue to do research on past and present human populations in order to improve our understanding in the future.

Can county-level net migration be predicted for areas larger than the Great Plains? The answer appears to be yes, at least for the United States, and perhaps for all of North America.

Ecological Feedbacks to Global Warming: Extending Results from Plot to Landscape Scale

John Harte

University of California
Berkeley, California

Physics-based climate models predict that during the coming century, global-averaged surface temperatures will rise significantly because of human-caused increases in the concentrations of greenhouse gases in the atmosphere (IPCC, 1996). We know little, however, about the ecological consequences of this warming, and we know even less about the extent to which ecosystem responses to warming will trigger feedback effects on the climate that will either enhance (positive feedback) or suppress (negative feedback) the warming. To reduce these uncertainties, since 1990 Harte and colleagues have been observing the biogeochemical and vegetational effects of heating a subalpine meadow.

Warming is achieved with overhead electric radiators designed to continuously mimic the model-predicted warming (see Figure 1.14). The five 3 meter by 10 meter heated plots and the five similar-sized control plots contain habitat ranging from a mixed shrub-steppe and grassland vegetational community along a semi-arid ridge down to a moist swale containing a diverse assemblage of forbs. The team has been monitoring soil temperature and moisture (every two hours at 5, 15 and 25 cm depths), floral productivity, phenology, and diversity, changes in net carbon storage above and below ground, soil mesofaunal biomass and species diversity, methane consumption rates, nitrogen pool sizes and turnover rates, and plant water stress.

We know little about the ecological consequences of climate warming, and we know even less about the extent to which ecosystem responses to warming will trigger feedback effects on the climate.

Figure 1.14

Overhead electric radiators heating plots at Rocky Mountain Biological Laboratory in Gothic, Colorado (photos by Susan Joy Hassol).

Among the major findings:

(1) heated-plot soils average 2°C hotter and 5 to 25% drier than controls and there is a sharp diurnal cycle in the temperature difference (up to 6°C warmer in midday) (Harte et al., 1995);

(2) the snowfree season is about 1 month longer in the heated plots (Harte et al., 1995);

(3) heating shifts the flora from forbs to shrubs such as sagebrush (Harte and Shaw, 1995);

(4) carbon is lost from the heated plots relative to the controls; the cause of this loss is a decline in litter input to soil rather than an increase in the soil decomposition rate in the heated plots (Saleska, Harte and Torn, 1997);

(5) heating enhances mesofaunal diversity and biomass in a cool, wet year and reduces them in a hot dry one (Harte, Rawa and Price, 1996);

(6) soil drying reduces methane consumption under relatively dry ambient soil conditions and enhances it under more moist ambient conditions (Torn and Harte, 1996).

These findings portend several important ecological feedbacks to climate change:

(1) A climate-change-induced alteration of the rate of methane consumption by soil microbes will alter the atmospheric concentration of this greenhouse gas. Results indicate that this feedback can be either positive or negative, depending on ambient soil moisture conditions.

(2) Because the albedo of vegetation differs from species to species, and from forbs to shrubs, the observed shift toward sagebrush dominance will alter surface albedo; radiometric measurements at the site indicate that this will result in lower albedo and thus the climate-induced shift in the composition of the vegetation community will result in a positive feedback to warming.

(3) The observed loss of stored ecosystem carbon in the heated plots implies a positive feedback to warming.

To extend the spatial and temporal generality of these findings, the critical question of scale must be addressed. In particular: How, and using what criteria for success, can results of manipulation experiments carried out at the spatial scale of experimental plots (~10-100 m2) and the temporal scale of NSF-funded studies (a few years) be extrapolated to the scales of concern (landscapes to global and decades to centuries)?

To extend the spatial and temporal generality of these findings, the critical question of scale must be addressed.

Naive extrapolation from plots to landscape entails simple multiplication by area. This may not be possible for either of two reasons:

(a) Edge effects resulting from the small size of experimental plots may render plot-scale results inapplicable to larger areas.

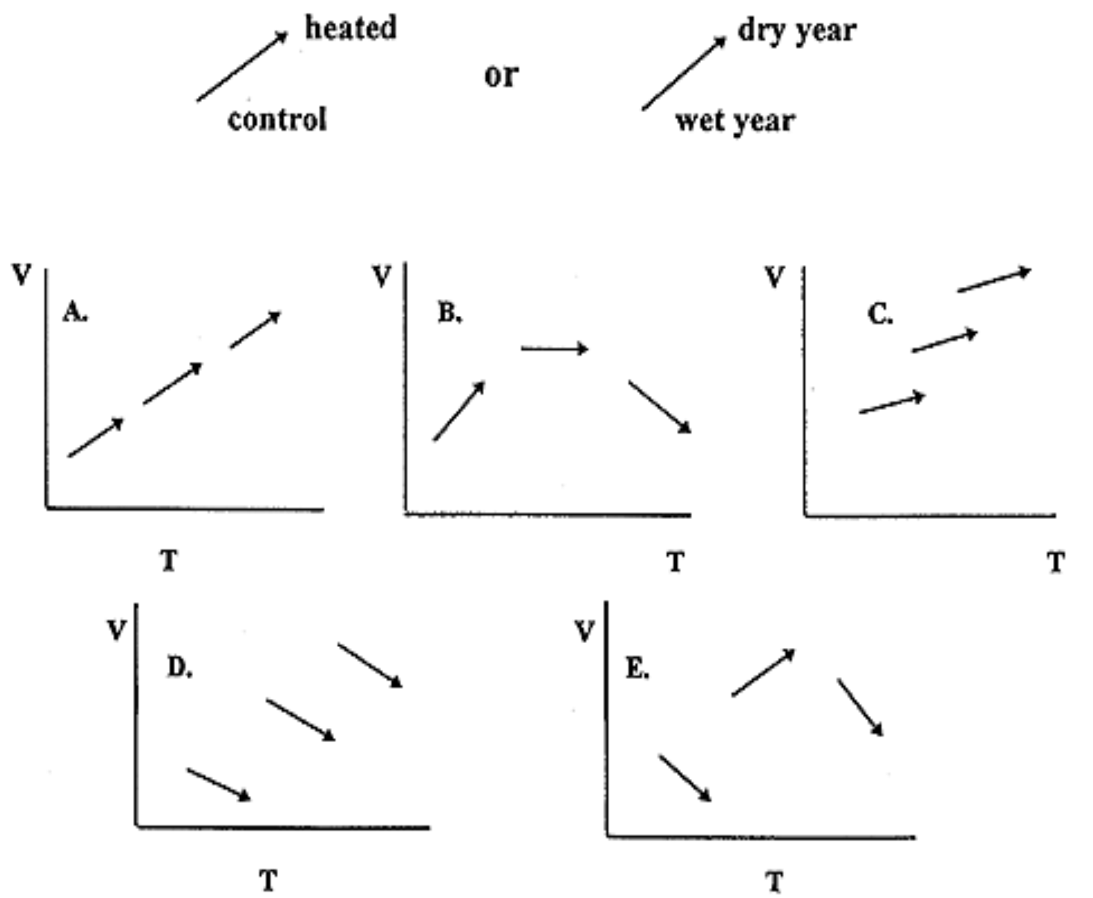
(b) Responses to climate change differ from one site to another within the landscape.

If reason (a) applies, no means of extrapolation may be possible, naive or otherwise; plot-scale results would be artifactual and irrelevant to larger areas. Harte and colleagues have developed and applied tests to show that the patterns of ecosystem response they have observed at the plot scale do not result from edge effects (see, e.g., Harte et al., 1996). The more interesting and likely impediment is reason (b); in this situation, extrapolation may still be possible, but rules for doing so have to be identified and tested. Confidence in those rules will be enhanced to the extent that a mechanistic understanding of patterns of response is developed.

A possible approach to improving naive extrapolation relies on information about natural variation in ecosystem parameters along natural climatic gradients. Under the assumption that ecological variation along natural climate gradients mirrors ecological responses to manipulated climate (i. e. , variation in space is a surrogate for variation in time), data from large-scale gradients can be used to predict large-scale ecological responses to warming. This, too, can fail, however, because of a mismatch in the time scales for response to relatively rapid anthropogenic climatic change and for slower adaptation to natural climatic variation along elevational gradients. Moreover, contingent factors that have little relation to climate variation along natural gradients may render ecological patterns of variation along those gradients irrelevant to anthropogenic climate change.

Extrapolation of plot scale results to larger areas may be possible, but rules for doing so have to be identified and tested.

Marv Waterstone, Danny Harvey, Don Wuebbles, and John Harte at the Gothic, Colorado site (photo by Susan Joy Hassol).



Confidence in these rules for extrapolation will be enhanced to the extent that a mechanistic understanding of patterns of response is developed.

Figure 1.15
Responses of an Ecological Variable (V) to manipulated (or interannual variation in) a climate variable (T) along a gradient of T.

Case A: Simple, universal response
Case B: Complex but coherent response
Case C: Same sign, but mismatched magnitude
Case D: Mismatched sign
Case E: No coherent pattern

These five graphs (Figure 1.15) illustrate some of the ways in which the space for time assumption can succeed or fail and point to ways in which rules for extrapolation can be identified and tested. The variable, V, is an ecological parameter such as the stock of soil carbon or the rate of sagebrush seedling establishment. T is an environmental variable such as soil temperature or moisture that both varies along a gradient and also is affected by a manipulation and perhaps varies interannually. The arrows describe the effect of the manipulation (here taken to be an increase in T) on V at particular sites. The base of the arrow is the value of V in the control plots and the tip of the arrow is its value in the manipulated plots.

The cases A through E pose a mix of declining opportunity and increasing challenge for scaling. Standard statistical methods such as analysis of covariance permit serial rejection of each of the cases A-D. For cases B-E, it is useful to search for underlying “hidden” variable(s) or contingent factors that explain these more complex patterns.

To apply this conceptual framework to montane meadows, Harte and colleagues have set up field sites and climate manipulations along an elevational gradient spanning a horizontal distance of 12 km and an elevational range of 350 m. As in the illustration, monitoring and climate manipulation are carried out at 3 sites along the gradient . Preliminary results suggest that the timing of the flowering cycle of plants along the gradient resembles cases A and C, depending on the individual species.

Soil carbon exemplifies a more interesting situation. It varies non-monotonically along the elevational gradient (arrow bases in case B), as does the biomass of grasses. Indeed, grass biomass and soil carbon correlate strongly across a range of scales from quadrats within plots, to plots within elevational sites, and across elevational sites. But graminoid biomass is unresponsive to warming, indicating that the long-term controls over soil carbon may bear little relation to the factors influencing soil carbon response to manipulated climate. The latter appears to be most responsive to forb biomass.

The AGCI group visits John Harte's experiment in Gothic, Colorado

Harte concludes that natural climate gradient analyses may not serve as a valid substitute for manipulation experiments in predicting how soil carbon will respond to global warming. Thus determination of the magnitude and even sign of this carbon-mediated ecological feedback to climate change will require further application of manipulation experiments.

Natural climate gradient analyses may not serve as a valid substitute for manipulation experiments in predicting how soil carbon will respond to global warming.

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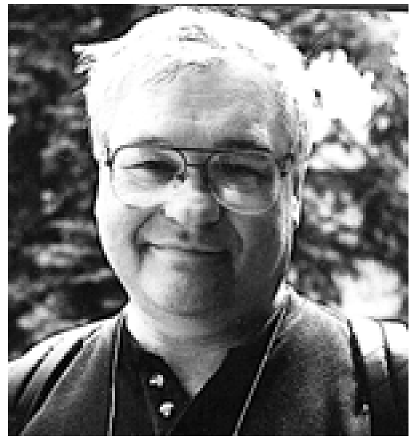
John Harte discusses his experiment with the AGCI group (photo by Susan Joy Hassol).

Turbulence in the Atmosphere and Oceans

Martin I. Hoffert

New York University
New York, New York



Hoffert discussed issues of scale with regard to turbulence in the oceans and atmosphere. Turbulence is an order of magnitude subject; there is no rigorous theory of turbulence. From a climate perspective, we are challenged by an atmosphere, oceans and Earth that are highly anisotropic (having different properties when measured along different axes or directions), with a ratio of 10 million to 1 in characteristic land scales. The horizontal and vertical dimensions and not comparable and fluctuations in all the fields are highly anisotropic in the large scale circulation that determines climate. How does turbulence enter into the large scale prediction of global climate? What problems exist and what can be elucidated through a better understanding of turbulence?

Small scale turbulence actually controls the large scale circulation of the oceans and is simply input into GCMs (not explicitly resolved).

Very small scale turbulence (eddy scale size on the order of 1 meter to a few meters, out of 4000 meters of ocean depth) is associated with vertical mixing in the oceans. This small scale turbulence actually controls the large scale circulation of the oceans and is simply input into GCMs (not explicitly resolved). Hoffert predicts that it will be many years before we can explicitly resolve this turbulence in computer simulations.

Equator to Pole Gradient

Earth has a poleward flow of heat carried by both the atmosphere and oceans; the equator would be far warmer and the poles far colder if this flow did not take place. This gradient is important to Earth's climate. As the climate changes, what happens to this gradient? The climate sensitivity question is a zeroth order problem: how much temperature change will be brought about by a doubling of carbon dioxide concentration in the atmosphere? The first order problem then is what happens to the equator to pole temperature gradient? How will the climate change at different latitudes?

Hoffert makes the case that the poleward heat flow is not being properly represented in GCMs; nor do current GCMs properly represent what we know from paleoclimate data: that tropical temperatures remain relatively stable while polar temperatures change much more dramatically.

Figure 1.16, for example, illustrates the equator-to-pole surface temperature difference relative to today's for two very different climates: (i) the middle Cretaceous 100 million years before present (100 MY BP) and (ii) the Last Glacial Maximum (LGM) 18 thousand years before present (18 kY BP). Note that temperature changes are relatively small near the equator, but large near the poles. This implies a much flatter equator-to-pole temperature distribution during hot periods like the Cretaceous, and a more non-uniform distribution during cold spells like the LGM. This is a paradox for the theory of eddy transport because large temperature gradients are

required by present theories to produce large poleward heat transports in the atmosphere and oceans. How therefore can a flat temperature gradient produce the large heat transport needed to create the "flatness?" The equator-to-pole temperature gradient is now about 45°C; it was less than half of this, about 20°C in the Cretaceous period of 100 million years ago.

Poleward heat flow is not being properly represented in GCMs.

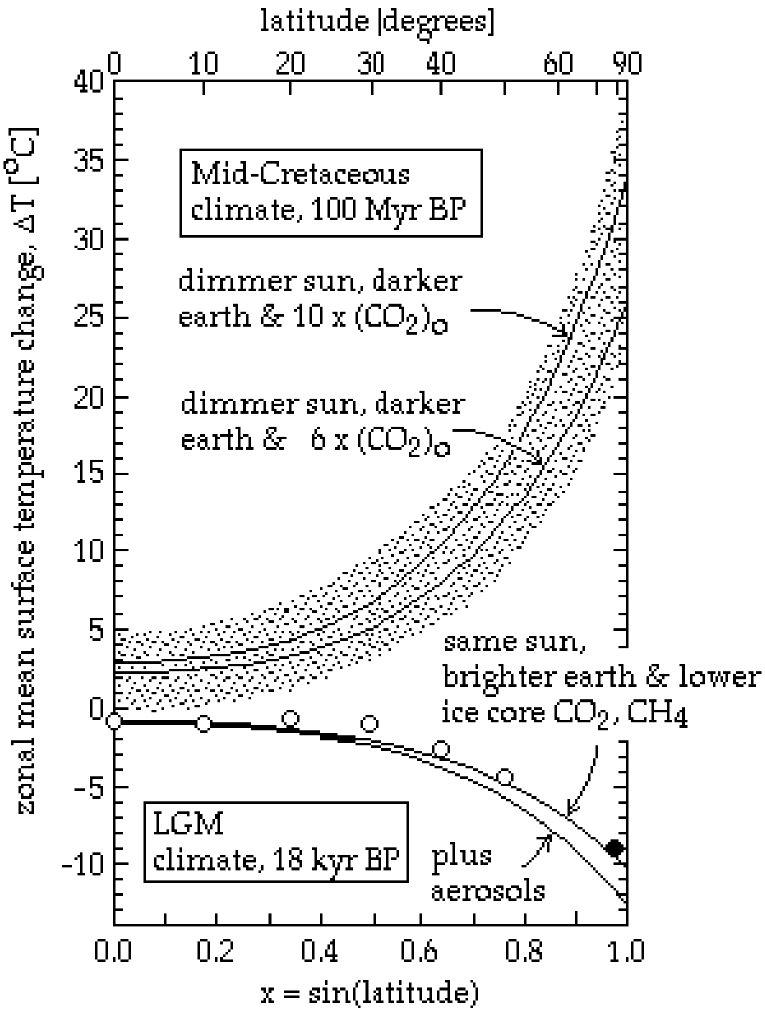


Figure 1.16

Equator-to-pole temperature response 100 Myr and 18 kyr BP. The stippled region is the range of Cretaceous climate response obtained by subtracting the present zonal mean temperature distribution from the 100 Myr BP temperature reconstructions in Thompson and Barron and averaging the two hemispheres. The LGM response is synthesized from CLIMAP sea surface temperature changes averaged for the hemispheres equatorward of sea ice every ten degrees latitude (f < 50o) denoted by and a high-latitude point from the Vostok ice core deuterium isotope record representing the air temperature change over the Antarctic plateau 18 kyr BP. The solid curves are zonal temperature responses of the mid-Cretaceous and LGM.

Another problem is the current parameterizations of turbulence in the interior of the ocean. What are the principle axes of turbulence and should we allow turbulence to vary with stratification in models? And where does the turbulence come from? Diffusivity is 50 times higher than would be expected given the properties of sea water. Why is this the case in the

interior of the ocean? The driving force of turbulence is shear flows a strong vertical gradient in current which can be caused by breaking internal gravity waves. Turbulence can also be caused by an instability associated with density. Any small disturbance can cause what is called “convective overturning.” Unstable potential temperature causes the flow to become violently turbulent to erase the gradient that created the turbulence. This is because a high density blob of fluid sitting above a low density blob in a gravitational field is unstable. This is called convective adjustment; it exists in both the oceans and atmosphere, and is built into current GCMs.

Turbulent eddies are regions where properties like temperature and salinity fluctuate relative to background currents. They are important in ocean dynamics because heat and tracers like carbon can be transported from one part of the ocean to another for example, from the surface to the deep ocean by turbulence. And they are not generally resolved in ocean models so they have to be represented by approximate equations (parameterizations).

In stably stratified situations (denser water below less dense water), like the ocean thermocline, turbulence comes from the breaking of internal gravity waves - waves associated with the stratification of the oceans and characterized by buoyancy frequency . These gravity waves are ubiquitous in the oceans and they come from different sources. Some may come from surface processes, but the turbulence of the boundary layer does not penetrate very deeply into the ocean. The ocean overturning time is about a thousand years so it takes hundreds of years for surface turbulence to reach the interior of the ocean. But turbulent eddies in the interior ocean decay on time scales on the order of a month. So something locally is creating the vertical turbulence. It is these internal gravity waves that locally produce shear which causes episodic turbulence.

It takes hundreds of years for surface turbulence to reach the interior of the ocean. But turbulent eddies in the interior ocean decay on time scales on the order of a month.

The thermocline (the first 500 meters of the ocean) is a region of the ocean where the temperature drops off relatively rapidly. The depth scale of the thermocline is controlled by the ratio of the vertical diffusivity to the mean upwelling rate of the ocean, and the upwelling itself depends on the vertical diffusivity. It is possible to write an equation for upwelling; the driving force of large scale overturning is related to the equator to pole temperature gradient and to some extent to the salinity gradient. All of this, Hoffert says, is the result of turbulence taking place on a spatial scale of a few meters which is not explicitly resolved in current GCMs. The poleward heat flow can be changed by an order of magnitude depending on this diffusivity.

What causes this interior mixing? Early work by Walter Munk refers to importance of the lunar tides for the spectrum of turbulence in the oceans. The moon pumps the gravity waves which are breaking and creating the turbulence in the ocean, controlling the depth scale of the thermocline, and hence, the ocean circulation. If lunar tides are indeed the source of vertical ocean mixing, it has important implications for the evolution of life on Earth because vertical mixing of nutrients and dissolved oxygen controls the amount of plankton and the rate of photosynthesis in surface waters. The present-day marine biosphere couldn’t survive without such mixing and would probably never have evolved in the first place without it. Since life began in the sea, life on Earth without the Moon (and lunar tides) might have evolved along quite different paths, if at all.

Hoffert then focused on the poleward heat flow associated with mean overturning of the thermohaline cells of the ocean which he says is the major component of poleward heat flow in the ocean. In the Cretaceous period, when the thermal gradient was less than half what it is

now, the poleward heat transport by eddies was one quarter of its current value, but it should have been more. This is a paradox. The Cretaceous equator-pole temperature gradient can't be reproduced with current GCMs.

Use of Simple Climate Models

Hoffert then discussed the use of simple climate models such as upwelling diffusion models (Harvey et al., 1997). Much policy direction comes from these simple models, perhaps more than the GCMs he says, so they are very important. Most coupled atmosphere/ocean (A/O) GCMs have to use flux adjustments because the models drift from initial conditions when run over long periods of time. This causes some to doubt the models' credibility. Hoffert says that the main advantage of GCMs is that they may eventually be able to help predict the regional distribution of climate change, but until then, simple models may offer more in the way of policy-relevant information.

Much policy direction comes from simple climate models such as upwelling diffusion models, perhaps more than the GCMs.

Data from nine points in time from the Cretaceous through the present demonstrates that the equator to pole temperature distribution flattens as the world gets warmer. Research by Hoffert and colleagues indicates that in order for this flattening to occur, there must also be an increase in poleward heat transport. (When diffusion was held constant in a model, the equator to pole gradient remained at the current value.) It is still an unresolved issue whether and why tropical temperatures remain relatively constant while the higher latitudes are more sensitive. This is a real challenge for turbulence theory.

Hoffert presented results from an upwelling diffusion ocean/climate model for 6 different assumptions about vertical mixing (Figure 1.17).

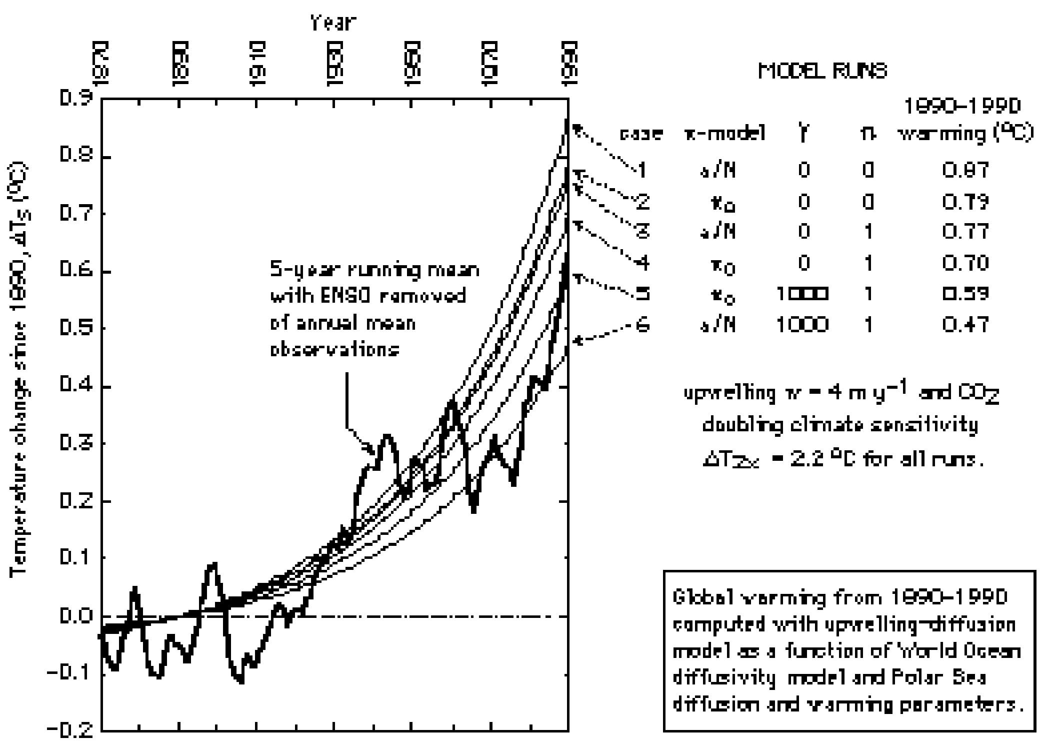


Figure 1.17

Observed global mean surface temperature variation relative to the year 1890 compared with global warming from 1870-1990 predicted from an upwelling-diffusion ocean/climate model for different World Ocean diffusion laws and Polar Sea mixing and surface warming rates.

These model results show that global warming for greenhouse gases input by human kind for the past hundred years can be significantly different for different models of vertical turbulent mixing which takes place at scales smaller than those which can be explicitly calculated by ocean circulation models.

And Figure 1.18 shows that present day model-derived oceanic heat flows are only about one-sixth of the 6 Petawatt (PW) peak heat flow to the poles implied by satellite data and about one-third of the 3 PW oceanic heat flow we expect as the residual of the total minus atmospheric heat flow. The apparently weak poleward heat flows of modeled oceanic flow components compared with residual implied values has been recognized for some time. It is extremely difficult to raise the poleward heat flow for fixed surface temperature, salinity and stress distributions to 3 or even 2 PW without invoking unrealistically large subgrid scale vertical diffusivity. In other words, the empirical evidence would suggest that the ocean was transporting half of the energy to the poles but none of the models show this.

The way turbulence is represented in current models is not realistic and this has important ramifications for the climate sensitivity predicted by these models.

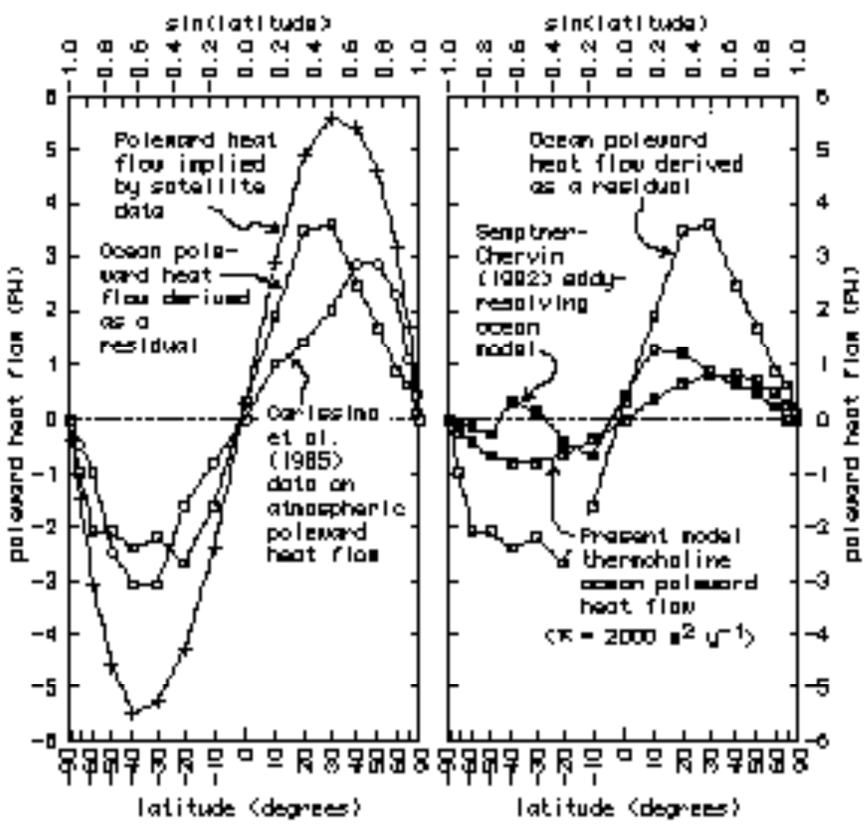


Figure 1.18

Global meridional heat flows in PW (1 Petawatt = 10 15 W) versus latitude (positive toward the North Pole). The left panel shows total, atmospheric and ocean heat flow derived as a residual by Carissimo et al. The right panel compares the Carissimo residual with ocean poleward heat flows computed by the Semptner-Chervin horizontal eddy-resolving Ocean GCM and Hoffert and colleagues' schematic model.

Conclusions

The way turbulence is represented in current models is not realistic and this has important ramifications for the climate sensitivity predicted by these models. This issue is particularly

relevant to issues of scale because processes at very small scales (on the order of 1 meter) ultimately control oceanic overturning and the equator to pole heat flux at the global scale. (There are 6 orders of magnitude difference between them). Roni Avissar says that this is the case in the atmosphere as well. In important ways, the small scale dominates the large scale. There is a fundamental problem in our understanding of the drivers of the global heat flux as our inability to replicate the equator to pole gradient in models shows. There is clearly a problem with accounting for the small scale at the global scale.

There is clearly a problem with accounting for the small scale at the global scale.

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Sea Ice and Issues of Scale

Lyn McNutt

University of Alaska
Fairbanks, Alaska

Sea ice plays an important role in the climate system as a result of the immense area it covers, its seasonal changes and heat flux effects, and its brightness, which leads to albedo feedbacks to climate. Sea ice is also significant for economic and habitat reasons, and can be important for modeling in ways that go beyond the physical system. McNutt discussed what sea ice is, how it grows, why and how we model it, problems with how it is modeled, and scaling and hierarchy considerations. She says that it is important, when modeling sea ice, to be very careful about jumping too many levels in scale without taking into account emergent properties and aggregate behaviors that come into play. She also stressed the need for more conscious validation of models and the need for more data collection and more accurate monitoring.

It is believed that sea ice in the Arctic Ocean plays a significant role in controlling deep water formation and thus the conveyor belt of oceanic circulation.

How Sea Ice Forms

Ice formation begins when platelets form as water reaches the freezing point; these platelets move with the wind and aggregate into pancake ice (1-3 meters). These pancakes then aggregate to form ice floes (large blocks) which can support snow. At this point, the ice floe starts to grow from the bottom and extrudes salt out. Then, as melting at the surface takes place, water puddles form which absorb incoming radiation because they are dark, and so they expand in size, becoming self-generating. There is constant brine flushing and constant change in albedo and heat flux from ocean to atmosphere based on the thickness of the ice. Sea ice is very dynamic and understanding these dynamics is important to our understanding of the effects of ice on climate.

Another type of ice is "fast ice" (see Figure 1.19) which grows out from the shore where platelets line up, and anchors itself to the sea bottom near the coast where it interacts with the sea ice pack. The length and extent of fast ice depends on how much the sea ice compresses into the shore. This fast ice is of interest because it behaves like a geological entity but moves so fast (up to 200 mm per second) that it can completely alter regional climate patterns.

Roles of Sea Ice

It is believed that sea ice in the Arctic Ocean plays a significant role in controlling deep water formation and thus the conveyor belt of oceanic circulation. The interplay between the Bering Sea and the Arctic Ocean leads to warm water formation that effects oceanic circulation, but general circulation models (GCMs) don't account for this interplay across the shelf. In the important fisheries of the Bering Sea region, ice has significant controls on fish habitat. Ice also allows for nutrient transport and creates whale habitat through openings in the ice. Contaminants in Russia River runoff are transported around the Arctic by sea ice, as is air

pollution, acid deposition, and particulate matter. In all of these ways, ice acts as a conveyor and the provider of key feedbacks to climate through atmospheric and oceanic circulation.

Figure 1.19 (left)

View of the Beaufort Sea from the edge of the fast ice, four miles off Point Barrow, Alaska (photo by Carl Byers).

The pollock fishery in the Bering Sea has been extremely productive since the 1970s. This is an example of how climate effects involving sea ice move all the way up the food chain.

An Arctic Climate Regime Shift

Air temperature and precipitation have risen in the Arctic since the mid-1970s and there has been a marked decline in sea ice extent (see Figures 2.6 and 2.7). There have also been serious changes in Bering Sea species distribution associated with this change in climate; these species changes lag the regime shift by about 3 years. Increased concentrations of greenhouse gases globally as well as Alusian Low and El Niño effects may be implicated in this regime shift which has effected the climatology of the entire Arctic. For example, the melt back of ice creates pools of bottom water and the relative heat of that water determines the longevity and growth rate for pollock. As a result, the pollock fishery in the Bering Sea has been extremely productive since the 1970s. This is an example of how climate effects involving sea ice move all the way up the food chain.

Sea Ice in the Physical Realm

In the physical domain, ice extent is important, as is its concentration, thickness, age, surface albedo, surface temperature, and roughness (both top and bottom). Ice extent changes seasonally and annually. Marginal ice zones are those that have ice in winter but no ice in summer. These seasonal ice zones (such as the Beaufort Sea) are very dynamic, have large annual variations, and have the most interplay with pack ice (and thus play a role in oceanic circulation patterns). In addition, the climatic regime shift mentioned above has caused additional changes in ice extent.

With regard to ice concentration, we must consider how much open water exists, where the leads are, and how they are oriented. Ice thickness and age are very important as well, and it is clear that the ice in the Arctic is thinning. The ice extent in summer has declined while in winter it hasn't changed much, but both summer and winter ice is getting thinner, and this changes the heat flux in the Arctic. The surface albedo of the ice depends on the extent of melt ponds making these a key feature. Roughness, both at the top and bottom surfaces of the ice, is also important.

The Role of Sea Ice in Habitat

Polynyas are openings in the ice that occur when winds blow the ice away from the shore. Polynyas are highly productive areas biologically. The ice edge is also very important from a habitat standpoint because fish and whales follow the ice edge. Shelf mixing is also significant because that is how nutrients and pollutants are transported around the Arctic. For example, after an oil spill, oil is sucked into the ice, rests in a layer there, and forms oil ponds in the melt water pools which are then distributed around the Arctic through shelf mixing.

Ice acts as a conveyor and the provider of key feedbacks to climate through atmospheric and oceanic circulation.

The Economic Role of Sea Ice

Sea ice has a large effect on navigation because in the Arctic re-supply is accomplished almost entirely by ship. Economically valuable fisheries and whaling are extremely connected to sea ice because, as mentioned above, fish and whales follow the ice edge. In addition, indigenous people rely on subsistence, and sea ice has large effects on their ability to subsist on harvests from their surroundings. Could climate change eliminate this entire way of life by reducing sea ice to the point that subsistence is no longer possible? Sea ice also effects development of resources such as oil and natural gas. Finally, ice in the Arctic has become a collector of contaminants that did not originate in the region. Through the global distillation effect, pollutants from industrialized areas in the lower latitudes have concentrated in the Arctic.

Sea Ice in Global Climate System Modeling

As explained above, sea ice is a very important and interactive climate parameter. Despite this fact, it has not been modeled effectively in general circulation models (GCMs). It has not been modeled responsively to the role it plays, but rather simply as a deforming slab, in most cases. There is, however, a simple and effective way to model sea ice, which was suggested by Zubov in 1943 and is widely used in operational sea ice forecasting. To determine the movement of sea ice, Zubov said, take 3 to 4 percent of the wind speed, 20 degrees to the right of the wind. Despite the fact that this is a very good rule of thumb for short-term modeling of sea ice, McNutt says, it has been ignored in GCMs (perhaps because it seems inelegant, she suggests).

How has sea ice been treated in global climate models? Sea ice has been modeled as an elastic, plastic, and/or viscous material in terms of its response to stress/strain. Elastic materials bounce back. If a material is viscous, its density increases but it doesn't come back if the pressure on it is released. Plastic materials break under sufficient pressure. Sea ice has been modeled mainly as a slab, and either as an elastic plastic material, a viscous plastic material or an elastic viscous material.

The earliest attempts to account for sea ice in GCMs involved simply treating it as a swamp - a thick layer that doesn't do anything. In such a model, the sea surface temperature (SST) is derived from the surface energy balance. The next level of sophistication involves a simple

mixed layer or slab ocean and accounts for a layer of sea ice, but one that is deformed with elastic, plastic or viscous properties, which is not a correct representation and does not account for interplay. Even the current best treatments are not realistic and do not properly include the interaction of sea ice with climate. Initially, the problem of sea ice treatment in GCMs was a resolution problem, but now it's a process problem, McNutt says.

Issues of Scale in Modeling Sea Ice

As discussed and summarized by session chair Danny Harvey, two distinct scaling issues arise in the treatment of sea ice:

(a) how the dynamic behavior of sea ice changes with scale, and

(b) determination of the scale at which atmospheric forcing of sea ice motion is most directly applicable.

Sea ice has not been modeled effectively in GCMs.

With regard to the first issue, an aggregate of ice floes behaves in ways that are quite different from the behavior of individual ice floes; in particular, ice behaves like a granular medium at the 0.1-1 km scale, while at a regional scale it behaves like a viscous fluid.

With regard to the second issue, the local velocity of sea ice cannot be directly related to the local atmospheric shear stress. Rather, the valid linkage is between regional atmospheric forcing and regional sea ice deformation. However, atmospheric forcing varies much more rapidly in time than the sea ice response, so the history of atmospheric forcing must also be taken into account.

Validation in Modeling

Sea ice parameters in GCMs are calculated internally making validation impossible, McNutt says. The fact that large scale information used in models is derived from existing models, rather than from actual mesoscale data, makes the models internally consistent, but not consistent with reality. Even for smaller scale models (5 to 20 km), parameters are derived from large scale models or generated internally from the models. McNutt believes that large scale sea ice behavior is probably being modeling reasonably well but that problems arise when aggregate behavior from the floe scale is applied to the mesoscale.

Scales of Change: The Climatic Impacts of Tropical Deforestation in Chiapas, Mexico

Karen L. O'Brien

Center for International Climate and Environmental Research (CICERO)
Oslo, Norway

There is a growing recognition that Earth's vegetation plays an important role in the climate system. The relationship between tropical forests and climate is one of the most challenging aspects of atmosphere-biosphere interactions, and the rapid rate of forest loss adds a sense of urgency to efforts to understand the implications of deforestation on climate. Although there is some empirical evidence to suggest that deforestation leads to changes in temperature or rainfall, the vast majority of the work on this subject has been conducted through simulations with mathematical models. General circulation models coupled with atmosphere-biosphere models provide increasing evidence that deforestation can significantly influence the climate at a number of scales.

Although modeling studies profess to consider the impacts of deforestation at the local, regional, and global scales, the underlying framework of the models remains unchanged at each of these scales. In fact, the same physical equations are assumed to govern the relationships at all scales, and it is simply the extent of spatial representation or analysis that is altered. The only empirical connections between real tropical forests and the models occur in the parameterizations included in atmosphere-biosphere models, which are often scaled up from observed measurements. However, the relationships among variables at larger scales may differ significantly from those occurring at smaller scales. In scaling up to higher levels of analysis, emergent properties may appear as a result of synergistic interactions taking place at higher levels of system integration, such as the regional or global scale. Further more, tropical deforestation usually results in a mosaic pattern of land cover, and there is evidence that the atmospheric response to a heterogeneous land surface is nonlinear (e. g., Pielke and Avissar, 1990). The issue of scale in tropical deforestation simulations has clearly not been adequately resolved.

In scaling up to higher levels of analysis, emergent properties may appear as a result of synergistic interactions taking place at higher levels of system integration, such as the regional or global scale.

One way of identifying such scaling influences is to compare modeling results with historical climate records collected in areas that have experienced significant deforestation. O'Brien presented the results of an empirical study of deforestation and climate change for an area located in the Selva Lacandona of Chiapas, Mexico (Figure 1.20), which forms part of North America's largest remaining tropical rain forest.

In this 19,000 km2 of mountainous terrain, a network of climate stations was established during the 1960s, prior to the onset of large-scale deforestation. Daily climate records from 18 of these stations (Figure 1.21) were analyzed, along with land cover changes evaluated using satellite imagery and field observations. A variety of deforestation patterns can be identified around the stations, varying from very little remaining forest cover to almost complete forest cover. Climatic change and deforestation were then considered together to determine whether a relationship between deforestation and climate change is evident at the local scale.

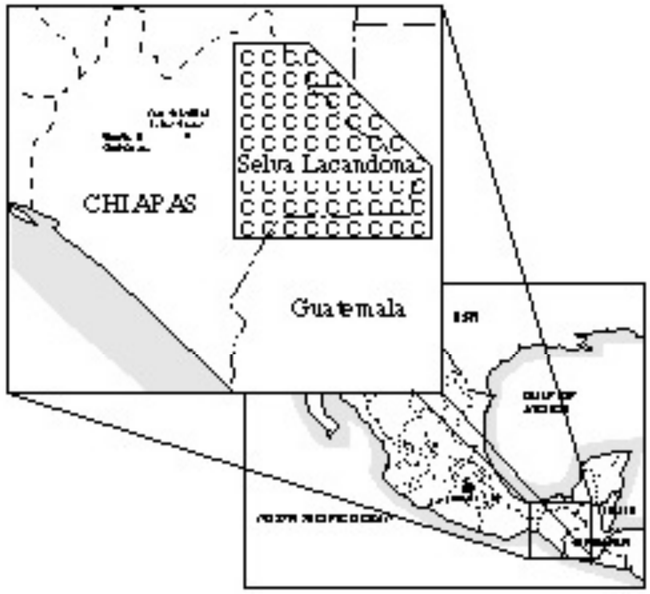


Figure 1.20
The Selva Lacandona region of Chiapas, Mexico

Tropical deforestation usually results in a mosaic pattern of land cover, and there is evidence that the atmospheric response to a heterogeneous land surface is nonlinear.

In this 19,000 km2 of mountainous terrain, a network of climate stations was established during the 1960s, prior to the onset of large-scale deforestation. Daily climate records from 18 of these stations (Figure 1.21) were analyzed, along with land cover changes evaluated using satellite imagery and field observations. A variety of deforestation patterns can be identified around the stations, varying from very little remaining forest cover to almost complete forest cover. Climatic change and deforestation were then considered together to determine whether a relationship between deforestation and climate change is evident at the local scale.

Comparisons among a tight network of highly correlated climate stations can be made based on the premise that variations in average weather show similar tendencies over fairly large regions. Synoptic-scale controls such as El Niño/Southern Oscillation (ENSO) events should exert a similar influence over all of the stations, regardless of the amount of remaining forest cover. Likewise, if global climatic change is evident, then it should appear consistently in the records of stations in close proximity to one another. If highly correlated stations' records exhibit differential trends, then local land cover changes can be considered a contributing factor (Karl and Williams, 1987).

Figure 1.21
Location of 18 climate stations in the Selva Lacandona

In empirical and modeling studies of deforestation and climate change there is a growing recognition that the simulated impacts of deforestation on the climate are regionally specific, in large part due to the different scales of the deforested areas (Zhang et al., 1996). While most modeling efforts have focused on the Amazon basin, more recent experiments covering Southeast Asia and tropical Africa show that the direction and magnitude of the changes may be very different outside of the Amazon region.

O'Brien's local scale analysis shows a strong tendency for maximum daily temperatures to decrease at climate stations exhibiting high deforestation, particularly to the northeast of the station. No changes in precipitation were observed. The temperature decrease is consistent with the results of modeling studies from regions outside of Amazonia, as is the lack of precipitation changes. The observed temperature decreases are driven by a decline in the number of extreme temperature events. This is not consistent with the modeling studies, largely because general circulation models do not adequately represent climate variability and extreme events. The results support the growing recognition that scale is a significant factor in determining the climatic impacts of land cover changes (Avissar, 1995; Raupach and Finnigan, 1995). One possibility is that landscape-level processes influence the climate in deforested areas, introducing local circulations that may not be evident at the microscale or at regional or global scales. There is mounting evidence that global, regional, local and even microscale processes represent different realms of analysis, and that simple extrapolations across scales provide an inadequate means of addressing the impacts of deforestation on the climate.

O'Brien's local scale analysis shows a strong tendency for maximum daily temperatures to decrease at climate stations exhibiting high deforestation, particularly to the northeast of the station.

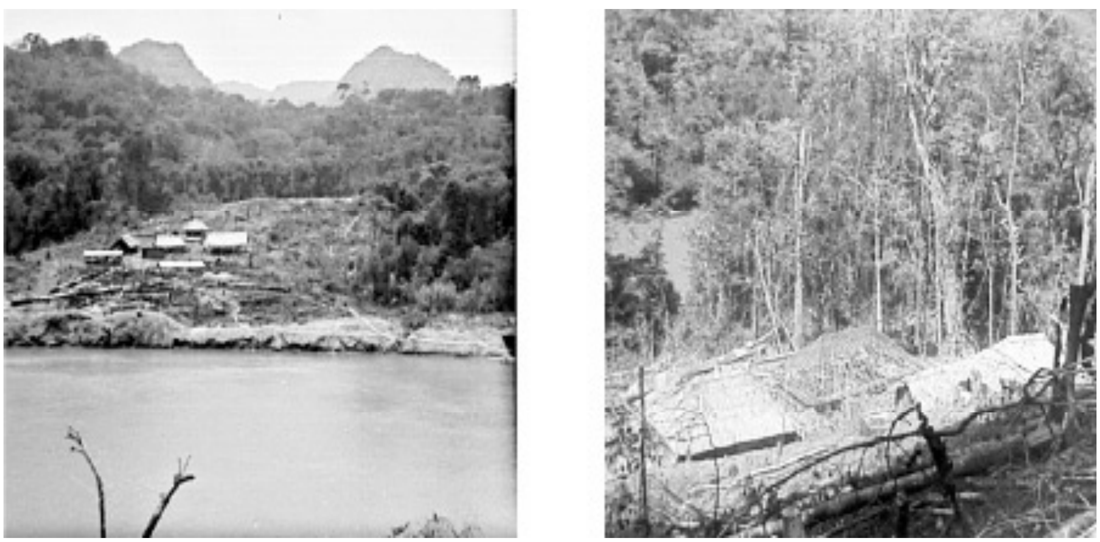


Figure 1.22
The climate stations El Colorado (left) and El Zapotal (right) under construction in 1970.

The Chiapas Study

One means of identifying the local impacts of tropical deforestation is to examine climate records from a tropical forest region and relate them to changes in the surrounding land cover. The Selva Lacandona of Chiapas, Mexico serves as an excellent site for examining such impacts. A network of climate stations was established between 1957 and 1970, when the forest was still a sparsely inhabited frontier (see Figure 1.22). Both mechanized logging and colonization got underway during the 1960s, initiating deforestation in dispersed areas. The

colonization process accelerated during the 1970s and 1980s, increasing the population and transforming the land cover in many parts of the Selva Lacandona. By the early 1990s, much of the land within the region had been claimed or titled, and forest surrounding many of the once-remote climate stations had been dramatically transformed. Nevertheless, some areas have experienced relatively little change, particularly those located close to protected areas. If local-scale land cover changes have an impact on the climate, then changes may be evident at some of the stations within the Selva Lacandona, and possibly absent at others.

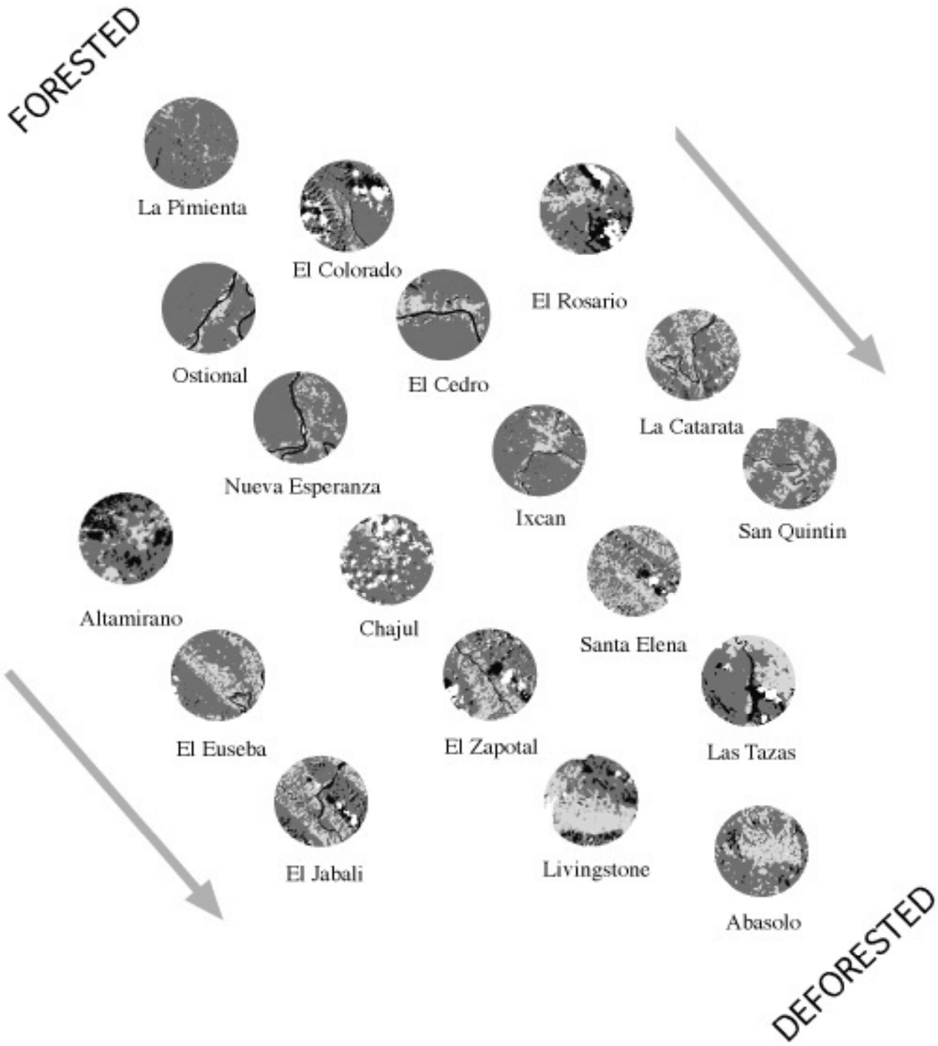
To evaluate climate trends in the Selva Lacandona, local and regional data sets were compiled and analyzed based on daily readings at 18 climate stations including maximum and minimum temperature and precipitation. First, the mean daily temperature was calculated by averaging the maximum and minimum temperatures. Next, the daily temperature range was calculated by differencing the daily minimum and maximum temperatures. The daily data were also used to calculate the annual average temperatures, temperature range and total precipitation, as well as frequency of temperature and rainfall extremes and the number of rainy days per year. Once assembled, the complete data sets were screened for biases that might appear as artificial climate changes. Finally, the data sets were subject to statistical analysis to determine whether a trend or discontinuity could be identified.

Deforestation in the Selva Lacandona reflects a dynamic process that is neither spatially nor temporally homogeneous, resulting in a mosaic pattern of land cover.

Deforestation in the Selva Lacandona reflects a dynamic process that is neither spatially nor temporally homogeneous, resulting in a mosaic pattern of land cover. Fields of secondary forest in various stages of regrowth are common. To interpret deforestation patterns, an historical analysis of the social driving forces was undertaken (O'Brien, 1998). A political ecology framework was used to understand the driving forces of deforestation, as well as the countervailing pressures for conservation. This analysis, as well as interviews with station personnel and archival photographs taken during the construction period, confirm that most of the areas were forested when the stations were established.

To provide quantitative estimates of deforestation, Landsat images were analyzed and interpreted. Multispectral Scanner System (MSS) and the Thematic Mapper (TM) data from several periods were acquired to create a time series of images for the Selva Lacandona. For each area extracted from the satellite images, the amount of forest change was calculated, along with the percentage of forest cover remaining in the most recent image. Results indicate that there is no clear-cut distinction between "forested" and "deforested" stations. Instead, deforestation appears as a continuum among stations (see Figure 1.23). The distinct patterns that emerge reflect the physical geography of the area, particularly the configuration of mountains and valleys. The location of roads and rivers also influences the patterns of deforestation.

In order to evaluate multiple interpretations of "local," areas of different sizes surrounding the climate stations were extracted for the analysis of deforestation. The regions were centered around the pixel where the climate station was located, and they included circles with radii of 0.5 km, 1 km, 3 km, 5 km, 10 km, and 15 km. Figure 1.27 is an example of this, showing deforestation around Chajul climate station in 1979, depicted at six spatial scales.



There is no clear-cut distinction between "forested" and "deforested" stations. Instead, deforestation appears as a continuum among stations.

Figure 1.23

Forest and cleared areas within a 3 km radius of climate stations in the Selva Lacandona. The light gray represents cleared areas; the dark gray represents forest; the white represents clouds; and the black represents terrain shadows, cloud shadows and water

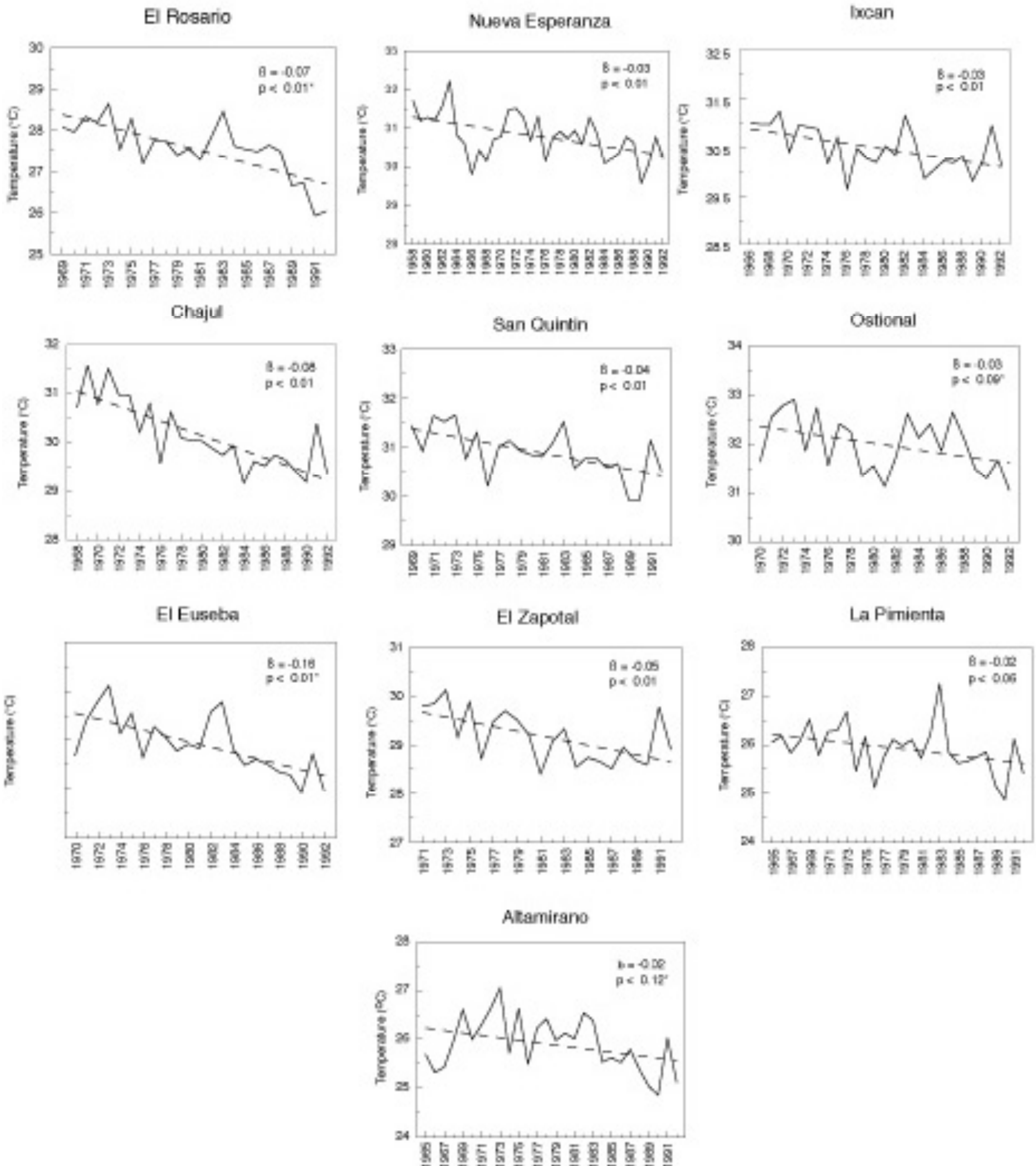
Maximum Temperatures

Maximum temperatures show the most interesting results in the Selva Lacandona. Ten stations reveal strong decreasing trends (see Figure 1.24). The trends are highly significant at seven of the stations, and striking but non-significant at the remaining three. It appears that 1973, 1983 and 1991 were relatively warm years at most of the stations, whereas 1976 and 1990 tended to be cooler. However, the temperature peaks in later years rarely attain the height of the earlier peaks. There is clear evidence that daytime temperatures are becoming cooler at some stations.

Figure 1.24

Maximum Temperatures: Decreasing Trends

Annual maximum temperature trends for ten climate stations in the Selva Lacandona of Chiapas, Mexico. The solid line represents the observed data; the dashed line represents the linear regression line. Estimated slope and probability values are indicated in the top right corner of each graph. An asterisk signifies that corrections for autocorrelation were made using an autoregression model.



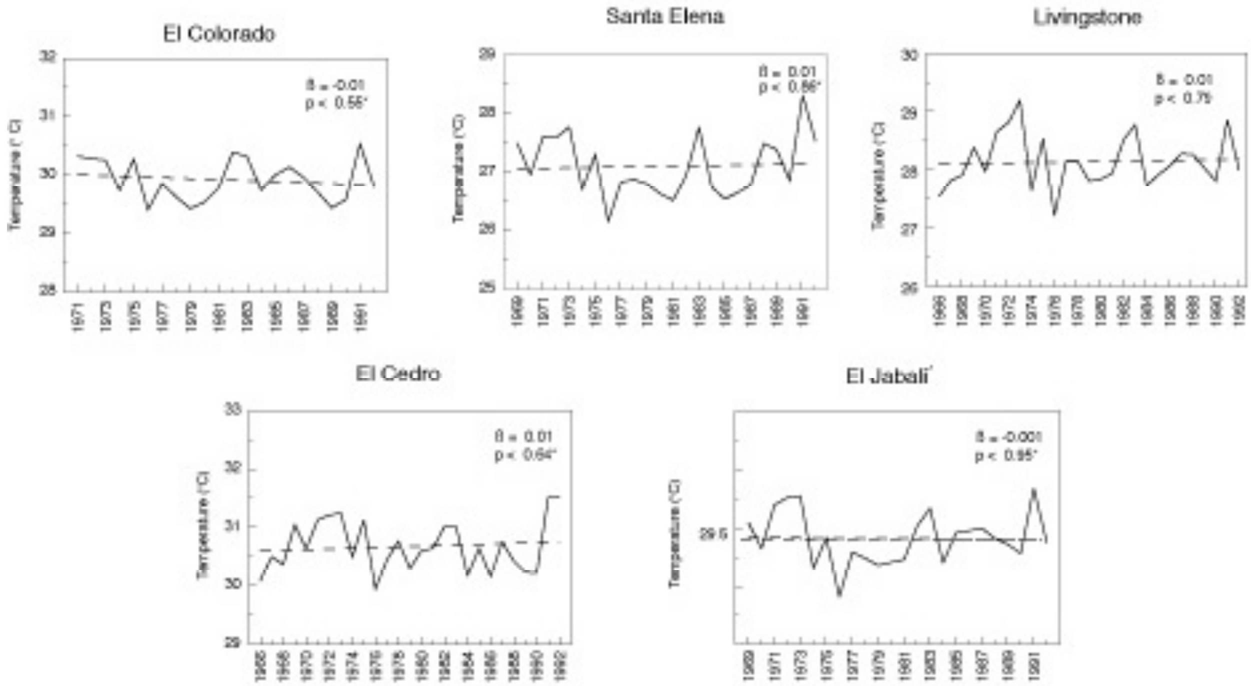


Figure 1.25
Maximum Temperatures: No Trends

Annual maximum temperature trends for five climate stations in the Selva Lacandona, Mexico.

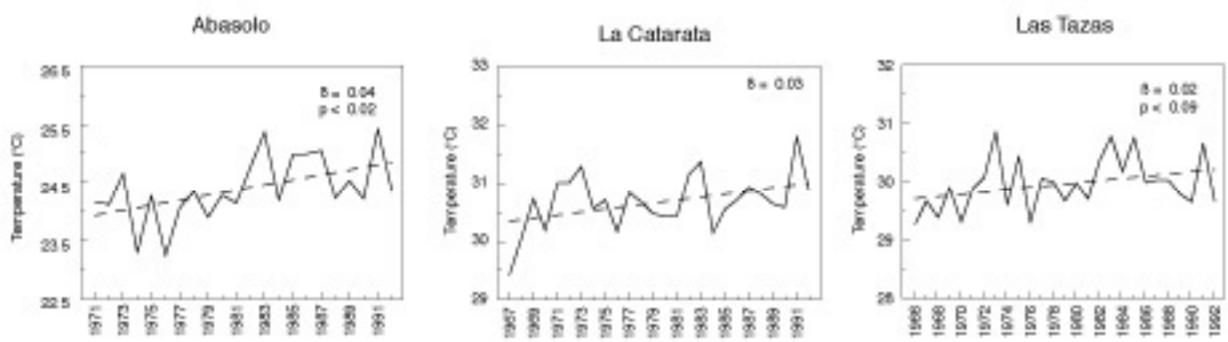


Figure 1.26
Maximum Temperatures: Increasing Trends

Annual maximum temperature trends for three climate stations in the Selva Lacandona, Mexico.

However, the cooling trends are not evident at all stations. For example, no changes are found in the climate records of five stations (see Figure 1.25). Similar to the stations discussed above, the years 1973, 1983 and 1991 stand out as particularly warm years, while 1976 and 1990 are relatively cooler. A small number of stations show increases in maximum temperatures (see Figure 1.26), and of these, only one trend can be considered significant and this one may reflect an abrupt change introduced by the construction of a nearby highway in the late 1970s.

A decreasing trend in daytime temperatures is predominant in the Selva Lacandona. To investigate the nature of this trend, daily maximum temperature extremes were examined. The number of hot days, defined as those days with maximum temperatures greater than one standard deviation above the mean of the time series, was calculated for each year. The year-to-year fluctuation of extreme days follows the mean maximum temperatures extremely well, but a decreasing trend dominates. Results suggest that the marked downward trend in maximum temperatures is driven by a decrease in the number of extremely warm days. There is a tendency for the number of extreme days per year to decrease, from 50-75 in the early 1970s to about 25 by the early 1990s. In contrast, there are no significant decreases in the number of hot days at three stations with no maximum temperature trends. The number of extreme hot days appears to be quite variable, with peaks and dips that correspond closely to the annual maximum temperature average.

Minimum Temperatures

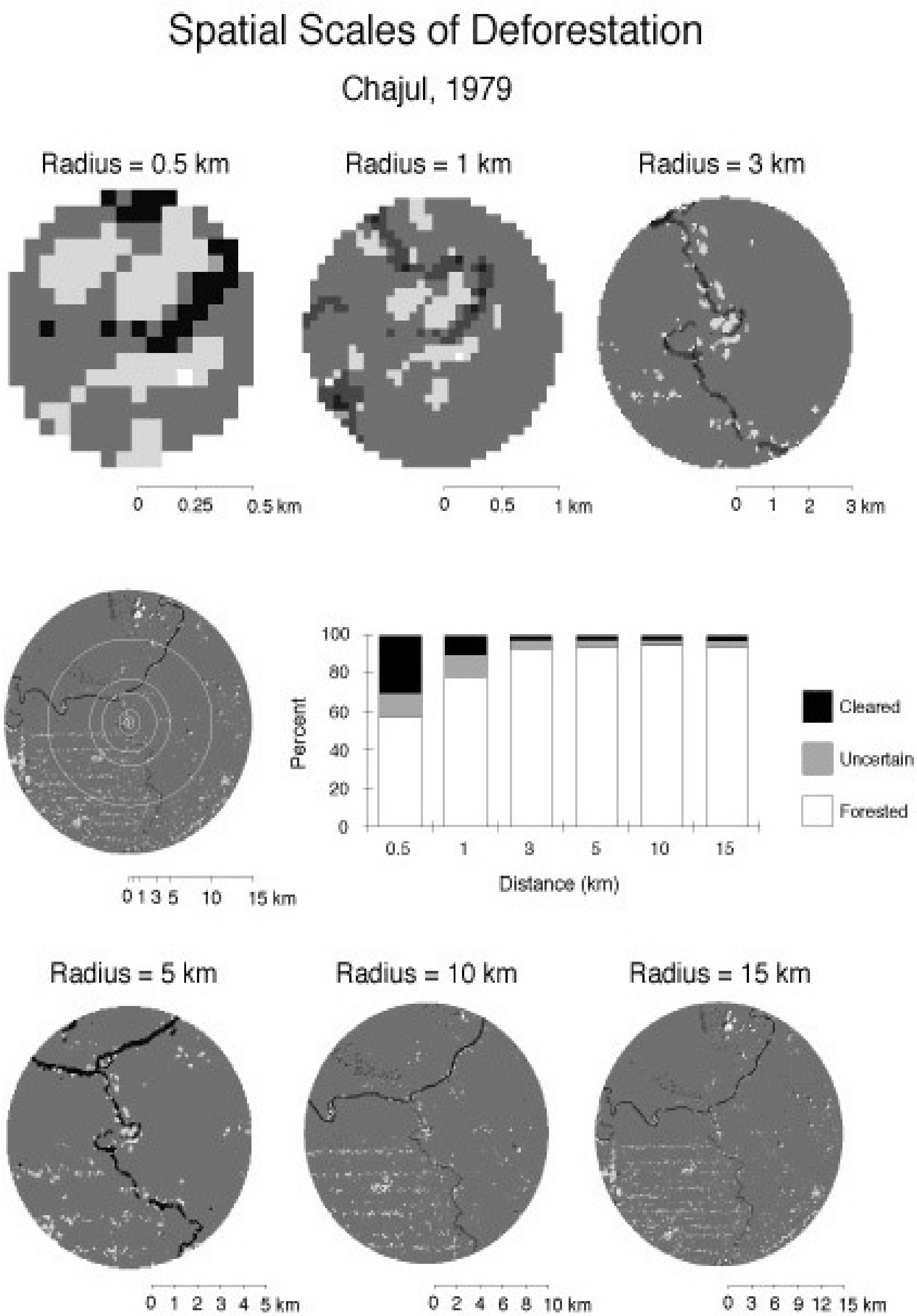
Just as maximum temperatures represent the daytime energy balance and circulation, minimum temperatures portray nighttime processes, typically in the early hours of the day. In marked contrast to the decreasing trends evident in maximum temperature records, minimum temperatures in the Selva Lacandona show an increasing trend at five stations. In three of these five stations, the trends are significant, whereas the other two are notable but non-significant. In contrast, six stations show no significant changes in minimum temperatures. The relationship among annual averages at the six stations appears to be generally consistent, with warmer than average years between 1978 and 1983, followed by cooler period between 1984 and 1989. An analysis of the daily minimum temperature extremes, calculated as those days with minimum temperatures greater than one standard deviation below the mean, revealed significant trends at only three stations.

In summary, there is a tendency for minimum temperatures to increase at some of the stations, but the majority of stations show no change. Four out of the five stations showing increasing trends also showed decreasing trends in maximum temperature (in one case, a non-significant trend). These stations should thus exhibit dramatic changes in the daily temperature range. Such changes are discussed below.

There is a tendency for minimum temperatures to increase at some of the stations, but the majority of stations show no change.

Daily Temperature Range

One characteristic of tropical climates is that daily temperature variations are larger than seasonal temperature variations. The daily temperature range, calculated as the difference between daily maximum and minimum temperatures, is influenced by proximity to oceans or water bodies, elevation, and cloudiness. Recent evidence shows that land use changes are closely correlated to daily temperature range in temperate areas. Four stations in the study area exhibited highly significant, quite dramatic decreasing trends. All of these stations exhibited a decline in maximum temperatures, and most of them show an increase in minimum temperatures as well. Four stations did not reveal changes in temperature range. Three out of the 18 stations show an increasing daily temperature range, but it is only significant at one.



In order to evaluate multiple interpretations of "local," areas of different sizes surrounding the climate stations were extracted for the analysis of deforestation.

Figure 1.27
Deforestation around Chajul climate station in 1979, depicted at six spacial scales

Precipitation

Precipitation is perhaps one of the most interesting variables, as changes in rainfall are frequently associated with deforestation. In this study, annual precipitation totals are highly variable with no clear trends. Between 1971 and 1977, rainfall appears to fall below the long-term average at most of the stations, whereas 1981 can generally be considered a peak year. The precipitation results are thus contrary to a widespread perception that rainfall has decreased in the Selva Lacandona (Arizpe et al., 1996). The discrepancy may in part be related to the date when colonizers entered the region; if they came in the early 1980s, it would not be surprising that short-term variability was perceived as a decreasing trend in rainfall.

Although total annual rainfall does not appear to have changed at these stations, it is possible that either the intensity of individual rainfall events or the number of rainy days per year has changed, and either of these could explain the commonly held notion that rainfall is decreasing. To consider this possibility, the number of extreme rainfall events was calculated for each station but no trends were observed at any of the stations. An analysis of the number of rainy days per year showed no trend at most of the climate stations in the Selva Lacandona, with the exception of four stations which showed highly significant increases, particularly during the dry season.

> Annual precipitation totals are highly variable with no clear trends, contrary to a widespread perception that rainfall has decreased in the Selva Lacandona.

Summary of Results

The patterns of both seasonal and annual changes in the Selva Lacandona can be seen in Table 1.28. This table shows the stations and variables that exhibit statistically significant (0.05 level) changes in climate, or trends which are interesting but not statistically significant (0.10 level). The results indicate that trends are clearly evident in the climate records of some stations and absent at others. The changes were considered in the context of large-scale processes that influence climate variability, such as ENSO. Global trends as might be expected under an enhanced greenhouse effect were also considered, as were local perturbations due to events such as the 1982 eruption of the volcano El Chichon in Chiapas (O'Brien, 1995). These types of influences should appear systemically throughout the region, and do not serve as explanations for the changes or lack of changes observed at the 18 climate stations.

Summary of Results for Climate Change in the Selva Lacandona

Station Name	Temperature											
	Minimum			Maximum			Range			Precipitation		
	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual	Wet
Chajul	+	+	0	-	-	-	-	-	-	0	0	0
El Zapotal	+	+	(+)	-	-	0	-	-	-	(+)	0	0
Ixcan	0	0	(+)	0	-	(-)	0	-	-	0	0	0
El Euseba	0	0	0	-	-	-	(-)	-	-	+	+	0
El Jabali	0	0	0	0	0	0	0	0	0	0	0	0
San Quintin	0	0	0	(-)	-	-	0	-	-	0	0	0
Abasolo	0	0	0	0	+	+	0	0	0	0	0	0
La Catarata	0	0	0	0	(+)	+	+	+	+	0	0	0
Las Tazas	0	0	0	0	(+0	+	0	(+)	+	0	0	0

Livingstone	0	0	0	0	0	0	0	0	0	0	0	0
Santa Elena	0	(+)	0	0	0	0	0	0	0	0	0	0
La Pimienta	0	+	(+)	0	(-)	(-)	0	-	-	0	+	(+)
El Rosario	0	0	0	-	-	-	-	-	-	0	0	0
Nueva Espera	0	(-)	0	0	-	0	0	0	0	0	0	0
Altamirano	0	0	-	0	0	-	0	0	0	0	0	0
El Cedro	0	(-)	(-)	0	0	0	0	(+)	0	0	0	0
Ostional	0	0	0	0	(-)	0	0	0	0	0	0	0
El Colorado	0	0	(+)	0	0	0	0	0	0	0	0	0

Table 1.28

This table shows the stations and variables which exhibit statistically significant (0.05 level) changes in the climate, or trends which are interesting (0.10 level, shown in parentheses) but not statistically significant.

The scale that seems to be most significantly related to trends in the climate record is captured by both the 1-km and 3-km circles.

The Issue of Scale

It was concluded that land use changes around the stations was the most likely influence on the climate. However, the issue of scale was still elusive. In particular, at what scale does deforestation impact the local climate? Deforestation was calculated for circles at a number of spatial scales around each station, and at four directions for each circle. To identify whether there was a relationship between the spatial and directional components of deforestation and the observed trend, a series of scatter plots was created. The plots incorporate information regarding forest loss, forest remaining, and changes in minimum and maximum temperatures at each station . The plots were then visually examined to see whether a relationship between deforestation and climate change emerged.

At the largest scales (15 km, 10 km and 5 km) and smallest scales (0.5 km), the stations exhibiting climatic changes appear to be randomly scattered. Given that a good amount of forest remains in the Selva Lacandona, particularly along ridges, this may not be surprising. A relatively deforested station appears to be heavily forested when considered in the context of the surrounding 10 or 15 kilometers. The scale of deforestation that influences the climate appears to be much more local, but not as local as the 0.5 km scale. Within this small area, most of the stations show little forest remaining.

The scale that seems to be most significantly related to trends in the climate record is captured by both the 1-km and 3-km circles. For the 1-km full circles, stations that showed forest loss and had less than 70 percent remaining forest cover often showed a decrease in maximum temperatures. Stations that showed afforestation, yet less than 80% remaining forest cover, also reveal such trends. At the 3-km scale, the stations that showed decreases in maximum temperatures or increases in minimum temperatures were generally deforested, with a remaining forest cover below approximately 85 percent.

There were, however, a large number of stations that showed a forest loss, yet no evidence of climatic change. To explain these anomalous cases, the directional components of deforestation were analyzed more closely. Each quadrant was examined separately for each spatial scale to

discover whether the anomalies could be explained. The northeast quadrant emerged as the one which best explains the anomalies. This is not surprising, given the important climatic role of the northeast trade winds.

Deforestation in the 1 km and 3 km northeast quadrants thus helps to establish a relationship between deforestation and climate change in the Selva Lacandona. At the 1-km scale, the northeast quadrant shows a large cluster of stations with a relatively large percentage of forest cover remaining, including four stations that did not show significant climate trends. When the 3 km circle is considered, five stations show a relatively large percentage of forest cover remaining in the northeast quadrant, despite a loss of forest during the period covered by the satellite images. The lack of changes at what otherwise appear to be deforested stations can perhaps be explained by this. The fact that two stations have less remaining forest cover at the 3-km scale can be attributed to the local geography. There are mountain ranges to the northeast of these stations, and the areas behind the mountains have been both colonized and deforested.

The amount of deforestation in the full circle surrounding the climate stations seems to be less important than the location of the clearings

Conclusions

This analysis suggests that the climatic effects of deforestation are influenced by the land cover at the 1-km to 3-km scale, particularly to the northeast of the station. In other words, the amount of deforestation in the full circle surrounding the climate stations seems to be less important than the location of the clearings. There were, however, some exceptional cases that are not explained by this.

This study does not address the mechanisms responsible for the observed changes. However, decreases in maximum temperatures have been observed in other parts of the northern hemisphere, as well as increases in nighttime temperatures (Karl et al., 1993). It has been hypothesized that these observations are related to changes in cloud cover. The results presented here suggest that landscape heterogeneity may be an important factor in determining the climatic impacts of deforestation. Indeed, the Selva Lacandona is a region of varied terrain, as well as varied land use practices. Forest regrowth plays an integral part in the land use dynamics in the area, resulting in a deforestation process that is neither linear nor concentrated.

These results do not contradict conclusions based on global modeling studies. Recent studies have emphasized that the impacts of deforestation are likely to be regionally specific, and that decreases in temperatures have indeed resulted from deforested simulations (Zhang et al., 1996). However, the results presented here do indicate that the issue of local-scale changes is more complex than the models suggest. There appears to be a minimum spatial extent of deforestation required before local climatic impacts can be discerned in the Selva Lacandona region. However, the magnitude and direction of the climatic trends seem to be influenced by the scale, distribution and geographic location of the clearings. Slope, aspect and terrain may also be important determinants of the climatic effects of deforestation. Different biophysical processes appear to dominate at different scales, and in different tropical regions, varying the nature of positive and negative feedbacks.

This research demonstrates that the nature of environmental problems is not one that can be addressed uniquely by models, satellite imagery, or aggregate national or global data sets. Neither can it be addressed by examining only microscale studies, local data or small-scale surveys. Instead, environmental change research demands an integrated approach that recognizes the complexity of scale, as well as the importance of analyzing data at a number of scales. Environmental research has matured to a point where generalizations can no longer

go unchallenged, and extrapolations can no longer suffice for an understanding of the impacts between deforestation and climate change across scales.

These results do not contradict conclusions based on global modeling studies, but they do indicate that the issue of local-scale changes is more complex than the models suggest.

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Scaling Ecological Dynamics

Garry Peterson

University of Florida
Gainesville, Florida

Scaling ecological processes requires understanding not only existing organizational hierarchies, but also the ways in which these hierarchies can reorganize.

One of the central aims of global change research is to understand how local actions can produce global changes, and how those global changes may impact specific, local sites. The translation of data or understanding from one scale to another involves a process of scaling. Scaling can take any number of forms ranging from simple averaging or interpolation, to the use of complex simulation models. Most global change research has used simple scaling methods that often inadequately map processes from one scale to another due to the complexity of ecological interactions.

Scaling difficulties arise for several reasons. Firstly, ecological processes often contain positive or negative feedbacks which make simple extrapolation difficult and/or inaccurate. Secondly, an ecological process that is important at one scale may be unimportant at another, so even if a process is understood, that understanding may prove meaningless at a different scale. Thirdly, processes at different scales interact, making it difficult to isolate objects for study, and limiting the generality of conclusions. Finally, cross-scale interaction may self-organize ecological processes, meaning that alternative ecological organizations may be possible that do not exist in the current ecosystem. This means that scaling ecological processes requires understanding not only existing organizational hierarchies, but also the ways in which these hierarchies can reorganize.

The complexities of scaling challenge global change researchers to develop methods that effectively transfer, or transform, measurements and information across spatial and temporal scales. As discussed above, translating understanding across scales using addition or integration only works over a limited scale range. For example, representing a forest as a group of average trees may work to predict aggregate properties of the forest under current conditions, but will not be very useful in understanding how the forest could change in the future. That would require assessing the responses of different tree species. However, attempting to scale processes by adding new processes and variables as the scale range of a model increases can work across small ranges of scale, but will become unmanageably complex across broader ranges of scale.

Ecological Self-Organization

One alternative approach to scaling is to focus on the self-organization of cross-scale structure. Systems theory proposes that systems organize around a few key variables, which suggests that identifying these variables and constraints under which they interact will allow a dynamic, parsimonious method of translating across scales.

Ecological organization is the result of the interaction among structures and processes operating at different scales. Ecologists have typically used hierarchy theory to analyze the effects of scale on the organization of ecological systems. However, hierarchy theory focuses upon the consequences of hierarchical organization, not on the processes that build and destroy hierarchy. Translating information across spatial and temporal scales requires understanding both how hierarchical organization is constructed and when it breaks down. The range of conditions under which a specific hierarchical organization maintains itself bound the application of scaling relationships derived for that hierarchical organization. These boundaries can be assessed by analyzing self-organizing processes that define ecological organization.

Self-organization occurs as nonlinear processes interact with one another and environmental heterogeneity. As small fast processes repeatedly interact with one another, these interactions may produce a larger slower structure that constrains the behavior of the small processes in such a way that they mutually reinforce one another. The “bottom-up” generation of such self-reinforcing structures provides a means of understanding how alternative hierarchical ecological structures can develop.

Ecosystems consist of the interactions between biotic and abiotic processes. Historical and current species extinctions and invasions have focused ecological interest on the role of species in the functioning of ecosystems. The variety of functions that a species can perform is limited, and consequently ecologists frequently have proposed that increases in species richness increases functional diversity. Often the analysis of ecological function has been confounded by scaling effects. Peterson suggests that ecological function and ecological organization can more clearly be understood when they are considered as emerging from a process of self-organization.

Ecological resilience emerges from the self-organized interaction of many different processes occurring at different scales.

Resilience as an Emergent Property

Species perform many different types of ecological functions. They may regulate biogeochemical cycles, alter disturbance regimes, or modify the physical environment. Alternatively, a species may regulate ecological processes indirectly, through trophic interactions such as predation or parasitism, or through functional interactions such as pollination and seed dispersal. On the basis of these ecological roles, species can be divided into functional groups. Ecologists have proposed that increasing the number of functional groups in an ecosystem increases the amount of change a system can experience before it reorganizes. This property can be described as a system’s ecological resilience.

Ecological resilience emerges from the self-organized interaction of many different processes occurring at different scales. Resilience is enhanced when ecological interactions that dampen disruption reinforce one another. Self-organization occurs as interactions that are mutually reinforcing tend to persist, while those that disrupt one another will tend to vanish. Such situations may arise due to compensation when a species with an ecological function similar to another species increases in abundance as the other declines, or as one species reduces the impact of a disruption on other species.

Different species operate at different temporal and spatial scales, as is clearly demonstrated by the scaling relationships that relate body size to behavioral ecology. While many species may inhabit a given area, if they live at different scales they will experience that area quite differently, since ecological structure and processes vary with scale. This cross-scale variation

provides different opportunities and costs to species that live at different scales. For example, a wetland may be inhabited by both a mouse and a moose, but these species perceive and experience the wetland differently. A mouse may spend its entire life within a patch of land smaller than a hectare, while a moose may move among wetlands over more than a thousand hectares (Figure 1.29). Scale separation reduces the strength of interactions between mice and moose relative to interactions among animals that operate at similar scales.

The ecological scales at which species operate often strongly correspond with average species body mass, making this measure a useful proxy variable for determining the scales of animals' perception and influence.

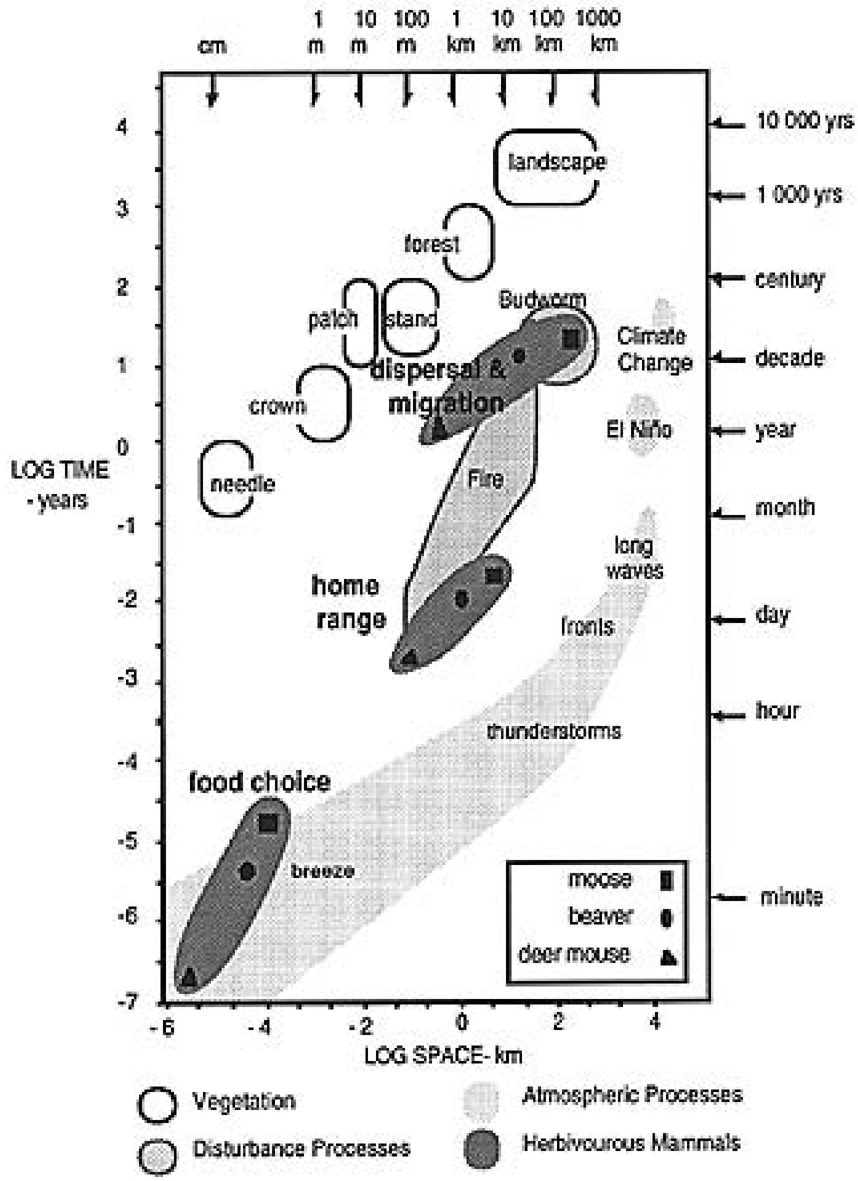

Figure 1.29

Time and space scales of the boreal forest, and their relationship to some of the processes which structure the forest. These processes include insect outbreaks, fire, atmospheric processes, and the rapid CO2 increase in modern times. Contagious mesoscale disturbance processes provide a linkage between macro-scale atmospheric processes and micro-scale landscape processes. Scales at which deer mouse, beaver and moose choose food items, occupy a home range and disperse to locate suitable home ranges vary with their body size.

Just as species can be divided into functional groups, species can be grouped based upon the specific scales that they exploit. The ecological scales at which species operate often strongly correspond with average species body mass, making this measure a useful proxy variable for determining the scales of animals' perception and influence. The resilience of ecological processes, and therefore of the ecosystems they maintain, may depend upon the organization of functional groups within and across scales.

If species in a functional group operate at different scales, they provide mutual reinforcement that contributes to the resilience of a function, while at the same time minimizing competition among species within the functional group. This cross-scale resilience complements a within-scale resilience produced by overlap of ecological function among species of different functional groups that operate at the same scales. Since ecological resilience is constructed by processes interacting across a range of scales, it also varies with scale and by process.

Different species operate at different temporal and spatial scales, as is clearly demonstrated by the scaling relationships that relate body size to behavioral ecology.

From this perspective, ecological resilience does not derive from redundancy in the traditional engineering sense of repeated function; rather it emerges from overlapping function within scales and reinforcement of function across scales. The apparent redundancy of similar function replicated at different scales adds resilience to an ecosystem, because disturbances are limited to specific scales, while if functions continue to operate at other scales, they are able to maintain a function. An example of this interaction between disturbance and resilience was described in South Florida. During Hurricane Andrew in 1992, mature mangrove trees were killed by wind damage, however many young mangroves survived. Many of these young mangroves were located in gaps caused by lightning. Local lightning disturbances provided the mangrove population with increased resilience to the large scale disturbance produced by Hurricane Andrew.

The analysis of ecological functions from a cross-scale perspective allows one to identify the scales over which an ecological process is robust, and over which it is brittle. For example, avian regulation of spruce budworm populations breaks down after budworm density exceed a critical level. This suggests that it is possible to identify scales of landscape change that may be most sensitive to changes in ecosystem function, or alternatively, at what scales critical ecological functions are in danger of being eliminated. Species turnover or process modification may not have immediately visible consequences, but they decrease ecological resilience to disturbance or disruption. For example, the loss of large birds from the forests of New Brunswick may reduce the scale range over which budworm predation is resilient, producing outbreaks at lower budworm densities.

The loss of species or processes produces ecosystems that are more vulnerable to ecological collapse, and reduces the variety of possible alternative ecological organizations . The loss of species that represent functional groups, especially large species that generate mesoscale vegetative patterns such as elephants, moose or tapirs, may eliminate possible types of ecological organization. There are suggestions that this may have occurred during the Pleistocene extinctions of mega-herbivores, and such losses appear to be particularly difficult to reverse, even if large scale ecological engineering projects are undertaken.

Conclusions

Translating either data or understanding across scales is often difficult. Peterson argues that moving across scales is difficult because the cross-scale interaction of ecological processes

produces dynamic, self-organized hierarchical structures. Viewing ecological organization as being composed of self-organized systems rather than being constrained by a complex set of top-down controlling processes allows one to identify opportunities for cross-scale ecological re-organization. It shifts the focus of scaling from looking solely at how change is transmitted across scales, to looking at what are the situations in which reorganization within a scale can occur, or entirely new levels of organization may form. Doing this provides a framework to identify what types of qualitative change are possible and plausible.

Focusing upon the self-organized dynamics of cross-scale interaction lays the ground work for developing a theory of novelty. One thing that is virtually certain about the consequences of global change is that, both to citizens and to scientists, its consequences are going to be surprising. When the resilience of existing systems is overwhelmed, processes and events that have never happened before will happen. Formerly unimportant processes or species will become important, and formerly fundamental things will lose their importance. This departure from the past suggests that theories that assume stable cross-scale organization are inadequate. Science requires a better understanding of how novel organization arises, and self-organization provides a framework upon which to build such a theory.

Moving across scales is difficult because the cross-scale interaction of ecological processes produces dynamic, self-organized hierarchical structures.

The Role of Land Cover as a Driving Force for Regional Climate Change

Roger A. Pielke, Sr.

Colorado State University
Fort Collins, Colorado

There is general agreement on the importance of land surface characteristics for microclimate. When a forest patch is clear cut, for example, daytime temperature near the surface in the clear cut area increases relative to the same height within the forest canopy. Up to 80 percent of Earth's land surface has now been modified by humans. Pielke discussed how such land use change affects surface properties, atmospheric structure, and thus climate, at a variety of scales.

Land use change affects surface properties, atmospheric structure, and thus climate, at a variety of scales.

Pielke reports that irrigated areas are 10 degrees C cooler than non-irrigated areas in Colorado. Effects from such a change extend upwards into the atmosphere. For example, more energy is now available for thunderstorm production than was previously the case. There is evidence that this irrigation effect is convecting cooler air into Rocky Mountain National Park creating changes in run off and species ranges. Are these trends due to land use change? There is not much pre-disturbance data so it is difficult to prove.

One data set that does exist is for south Florida. Data from 1900 through 1973 coincide with widespread fragmentation and other dramatic changes in the landscape. Limited observational data indicate that rainfall has decreased in the interim during the rainy season. No trend is seen at Key West, far away from the highly disturbed area and Fort Lauderdale shows a slight increase. There appears to be a spatial pattern to the change. Model results are consistent with the observed changes and suggest that decreased rainfall since 1900 may be due to land use changes. The area of maximum rainfall is smaller and total amount of rain has decreased. This demonstrates that climate is sensitive to landscape changes on this scale.

The importance of landscape on mesoscale and regional scale weather and climate is also seldom questioned. For example, O'Brien (1995) has documented how deforestation in part of Chiapas, Mexico has resulted in an altered climate from what occurs in the undisturbed forested region. Pielke et al. (1997), as illustrated in Figure 1.30, demonstrate the very significant role that land use has in generating thunderstorms. In Figure 1.30, identical initial and lateral boundary condition meteorology were used; the only difference was that in the bottom simulation, a short grass prairie was assumed, while for the top simulation, the current heterogeneous landscape was prescribed. The use of the current landscape in the model is a necessary condition for a realistic simulation of thunderstorm activity in this region.

In another example of the effects of landscape on weather and climate, Pielke points to a burn map in a boreal forest in Canada in which 16 percent of the landscape is in a recently burned environment. The burned areas are darker, resulting in preferential development of thunderstorms nearby which in turn cause more fires, generating a positive feedback with climatic effects.

Human modification of the landscape has affected rainfall, generation of clouds, and the formation of tornadoes and thunderstorms.

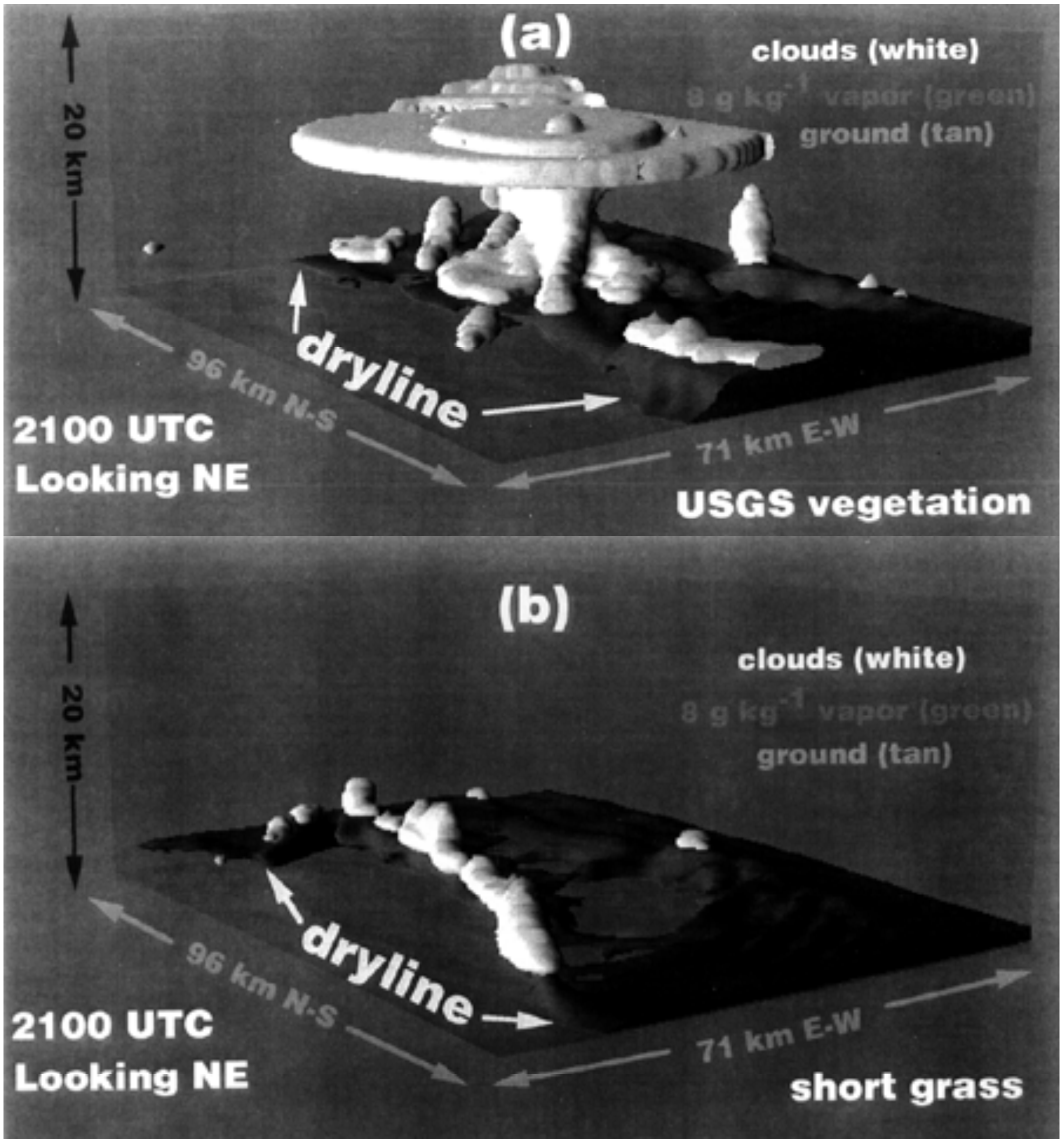

Figure 1.30

Model output cloud and vapor mixing ratio field on 15 May 1991. Figure (a) shows convective storm development with "actual" land cover derived from USGS data. Figure (b) shows convective storm development treating the land surface as native shortgrass steppe. (From Pielke et al., 1997)

In the Great Plains and the Texas Panhandle a correlation appears between heavily irrigated areas and tornadoes. In western Kansas, where center pivot irrigation is common, a mesoscale regional atmosphere modeling system has been used to simulate a day when a tornado formed (see Figure 1.30). A model run using the current landscape is compared to a model run using the natural landscape with the same meteorological conditions. Results indicate that the tornado formation is related to the current landscape. The implication of such research is that human modification of the landscape has affected rainfall, generation of clouds, and the formation of tornadoes and thunderstorms. Land use changes may also affect climate at larger scales, as the

landscape has been fragmented and the type of vegetation has changed from tall grass prairie to crop land in states like Kansas.

At the continental scale, Pielke reports that model simulations at 60-km grid spacing were used to compare U. S. climatic patterns under the conditions of estimated natural vegetation with the those of the current landscape in which huge changes in vegetation distributions are apparent. When this model is run for one month, forced with current conditions, changes at the scale of the United States are apparent. Did landscape changes cause such changes as the observed warming in the Great Plains, and changes in wind speed and relative humidity? Pielke says that sensitivity experiments indicate that weather and climate are indeed sensitive to the landscape at the scale of the U.S.

Even on a global scale, regional landscape changes, in the tropics in particular, alter climate thousands of miles away in the mid- and high-latitude polar jet flow. In a 1996 study by Chase et al., long-wave tropospheric wind flow was shown to be substantially altered when current, as contrasted with potential, leaf area index (LAI) was specified as a lower boundary condition in the NCAR CCM2 general circulation model (GCM). Regional precipitation patterns were also changed in the model over southeast Asia as a result of the model simulated change in LAI. It was the change in the GCM-modeled thunderstorm activity, that resulted from the LAI change, that teleconnected to the higher latitudes and changed the polar jet flow. The conclusion from these and other studies is that land use plays a significant role in local, regional and global climate.

Vegetation dynamics interact with climate and weather through a coupled nonlinear interaction.

Interaction

Atmosphere-land cover two-way interactions also occur. These interactions can be on the diurnal scale, on the seasonal scale, and on the multi-year time scale. On the seasonal time scale, prescribed LAI significantly affects the meteorological model simulation of temperature and precipitation. Correspondingly, the prescription of temperature, and particularly precipitation, dramatically affects a biogeochemical model simulation of LAI and root density.

Since both the meteorological and ecological models are strongly influenced by what are dependent variables in the other models, this feedback must be considered in any climate simulation. The conclusion, therefore, is that vegetation dynamics interact with climate and weather through a coupled nonlinear interaction.

Predictability

In any nonlinear system, the time period of predictability is dependent on the degree of nonlinearity and the level of accuracy with which the feedbacks within the system can be represented. In the context of the climate system, the temporal limits on climate prediction are determined by (i) our understanding and ability to represent quantitatively the interactions between each important aspect of the Earth's climate system; and (ii) the degree of nonlinearity of these interaction. In the context of regional and global climate prediction, these limits have not been determined. Moreover, as discussed above, global and regional scale climate effects cannot be considered independently, but interaction across scale must be considered.

Conclusions

In terms of global climate predictability, Pielke asserts that accurate forecasts of future global and regional weather regimes beyond this time period are unattainable. He thus suggests

that a vulnerability/susceptibility approach to climate change (with the inclusion of other environmental stresses) should be adopted. Such a procedure avoids the riskier approach of assuming we can forecast the future climate and its interaction with other environmental factors.

A second conclusion is that the use of land surface weather records to detect regional (and therefore, global) climate change/climate variability must include the influence of land use change over time on the record. Deforestation, and agricultural and grazing changes, for instance, must be included. The use of surface weather records in heterogeneous regions also requires that an assessment of the representation footprint of what the weather record is measuring be determined. This assessment must necessarily include microclimate and mesoclimate effects.

In any nonlinear system, the time period of predictability is dependent on the degree of nonlinearity and the level of accuracy with which the feedbacks within the system can be represented.

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Measuring Environmental Values and Environmental Impacts: Going from the Local to the Global

Dale S. Rothman

University of British Columbia
Vancouver, Canada

Measuring the impact of global change depends critically upon our ability to measure the impacts of local changes and our ability to aggregate these across individuals, sectors, regions, and time. Difficulties are presented at each of these stages. There are strong philosophical and practical concerns in measuring environmental, health, social, and economic impacts even at the very local and individual level. Aggregating these across commodities, individuals, sectors, regions, and time runs afoul of our inability to make interpersonal and intergenerational comparisons, requiring significant and weighty value judgments to be made.

Different people may very well value the same impact quite differently. How then does society add all of these values up?

Rothman began by describing two studies he was involved with in recent years. The first, with the World Resources Institute, looked at the productivity of electric utilities and pulp and paper mills in the U. S. The researchers sought to point out that arguments implying that the rate of growth of productivity in these sectors had been declining due to environmental regulations were misleading because they considered only the "good" output of these sectors (electricity, paper, etc.) and ignored the "bad" output (air and water pollutants). To make this argument in the context of standard measures of productivity, they faced a particular quandary: what is the monetary benefit of reducing a unit of air or water pollution? In the second case, Rothman and colleagues were asked to prepare a report for Environment Canada answering the question: what would be the costs to Canada from climate change if no international agreement were reached and emissions of greenhouse gases continued unabated? Not surprisingly, and probably much to the chagrin of those who asked the question, their answer had a large element of "it depends."

These examples illustrate a common problem faced in the study of environmental and global change. Aside from the fact that we often do not know precisely what the impacts of our actions are on natural and human systems, even if we did, how do we translate these into measures upon which social and political decisions are commonly made? These measures tend to be, although they are not exclusively, monetary. Compounding this problem is that different people, as individuals, residents of a particular region, members of a particular economic sector, or members of different cultural groups, may very well value the same impact quite differently. This is further exacerbated when the impacts spread across generations. How then does society add all of these values up? And is the total value merely the sum of the individual values?

Rothman briefly described some of the key issues in the measurement of values, particularly for those things to which a price, as normally conceived, cannot be attached. He pointed out, in particular, the ways in which the scale at which goods and services are considered can affect the value attached to them. In this context, he addressed issues of interpersonal comparisons of utility and measures of social welfare. Utility here refers to some overall measure of an individual's well-being, which is determined, in large part, by the values attached to particular

goods and services. Social welfare represents some aggregation of these individual utilities across all members of a society.

He then addressed an issue of particular concern to global change research - the aggregation of values across time. The key issues here are those of changing values, and the concept of discount rates and their relationship to intergenerational equity. He also commented on the problems posed by scaling for assessments of the impacts of environmental and global change. He stressed the importance of being open and honest about these difficulties and the inherently normative and subjective nature of addressing them.

What is to be Valued and How is it to be Measured?

Categories of Values

The scale at which goods and services are considered can affect the value attached to them.

Over the years, economists have identified five different kinds of value: direct use values, indirect use values, option values, existence values, and other non-use values . Ideally, all of these values would be represented in the price of a good or service sold in an open, competitive market, in which the external impacts of the production and use of the item have been taken into consideration. Under these conditions, the price of a good would provide an accurate estimate of its economic value. In reality, these conditions are not met more often than they are - many items are not bought and sold, many markets are neither open nor competitive, and many externalities are not considered in the pricing of goods or services.

Economists have developed a variety of techniques for assigning economic values to goods and services for which there are no price-fixing markets. Economic value can be estimated through the price of proxy goods or services, often the cost of replacing the specific good or service of interest. Techniques to assess value via indirect markets exist, such as the travel cost method, which derives monetary estimates from data on costs of traveling to visit a particular recreational site or engage in a particular activity, and hedonic pricing methods, which attempt to decompose property and wage differentials into components that capture the use value of non-market goods such as air quality or mortality risk. Direct methods, such as contingent valuation, have also been developed in which artificial markets are created by directly asking people what they would pay for normally unpriced goods or be willing to accept as compensation for their removal.

Though accepted by many within economics and other disciplines, these valuation techniques remain problematic in many situations. Many, if not most, existing markets are not free and do not consider externalities. For price to accurately represent economic value also requires that other, fairly strict requirements be met. These include the existence of a world of rational agents, who are perfectly knowledgeable about the consequences of their actions and able, therefore, to act consistently in a way that maximizes their individual utility. Critics complain that human behavior hardly ever lives up to this assumption. People do not understand the systematic effects of their behavior or the costs associated with various trade-offs. Other, non-economic values, such as family, community, and religion, are important as well, but economic valuation, as opposed to other, more qualitative forms of value elicitation, is not well suited to representing them. These other considerations make economic valuation very difficult, if not offensive to many.

This difficulty is reflected in the work that has been done to date on estimating the effects of global and environmental change. Of the five types of economic value mentioned above,

the farther one moves away from direct use values, the less effort has been put into including these values. Some are even categorically excluded. For example, the forthcoming study by Mendelsohn and Neumann, which in many ways represents the state of the art, omits "non-market impacts, such as health effects, aesthetics, and some ecosystem impacts." These categories include some of the most severe effects, and an economic valuation that omits them will systematically underestimate the costs of climate change, providing an incomplete and distorted basis for policy making.

Incommensurability and Problems with the Notion of a Single Yardstick

Valuation generally implies the reduction of values to a common metric. In many cases, this metric is dollars or some other form of currency. The use of a common metric contains within it the very significant assumption about the substitutability of very different items. Differences of opinion about substitutability underlie many of the debates about long-term development and environmental degradation. This issue has been extensively discussed in the sustainable development literature and was raised in the IPCC Second Assessment Report.

Many, if not most, existing markets are not free and do not consider externalities.

The notion that everything can be made commensurable and reduced to a single currency is quite an anathema to many. If a dollar value can be placed on both a barrel of oil and a human life, does this mean that a sufficiently large number of barrels of oil can substitute for a human life? Can the extinction of a species be compensated for by placing the assets earned from its extinction in a bank and accruing interest on these assets? Klassen and Opschoor (1991) argue that, "values go beyond wants: values form a hierarchical system of separate and partly connected values at different levels. This hierarchy implies that values cannot be reduced to a single yardstick."

Other Aspects of Scale in Measuring Values

Another important scale-related concern, also associated with substitutability, relates to the physical scale at which the analysis is undertaken. This commonly arises in the case of trying to estimate the value of a particular site for recreation, such as a lake. Depending upon the presence or absence of viable substitutes, i. e. other lakes, which depends in large part on their physical proximity and whether they are included in the scale of the analysis, the value of the lake can differ markedly. In general, the more substitutes, the lower the value. Similarly, in analyses of global change, the impacts of forest loss or declines in agricultural productivity will differ greatly depending upon whether the analysis takes a local, national or global perspective.

Because economic valuation of global and environmental change is so difficult, it has only been attempted for a limited set of goods and services and a limited set of values in a limited number of areas. In particular for climate change, most of the work has focused on the United States. Many of the estimates for other regions are based upon transferring U. S.-based estimates to these very different locales. The process of extrapolating values to places other than where the original analysis was performed is called "benefits transfer" in the economic literature.
A limited amount of work has been done to explore techniques to take into consideration differing biological, societal, and economic structures, as well as cultures and values. However, especially in the case of global environmental change, these structures, as well as the extent of the actual physical changes, fall well outside the range over which the original estimates were made.

Going from Individual to Societal Measures of Value

There has been a long-running debate in economics over the ability to develop aggregate societal measures of welfare that are consistent with notions of individual utility. Three key elements that present a difficulty in doing this are interpersonal comparisons of utility and the existence of societal values that lie outside of measures of individual utility. Less from an individual, and more from a sectoral perspective there are also interactions that may be missed in simple aggregations.

Interpersonal Comparisons of Utility

Can the extinction of a species be compensated for by placing the assets earned from its extinction in a bank and accruing interest on these assets?

For a wide range of reasons, different individuals may place quite different values on the same impact. Similarly, they may rank order the same set of choices, e. g., bundles of goods or policy actions, very differently. More importantly, there is no clear means by which to make quantitative comparisons between individuals' utilities. These present significant problems for any attempt to aggregate from individuals to a larger group to determine either a measure of welfare or a rank ordering of choices for the group as a whole.

Kaldor (1939) and Hicks (1939), in two famous articles, presented the notions of Pareto improvements and Potential Pareto improvements, which seemed to provide a way around these dilemmas. A Pareto improvement represents a change in which no individual is made worse off and at least one is made better off. In a Potential Pareto improvement, certain persons can be made worse off, as long as the potential exists for a redistribution to occur after the change such that no individual is made worse off and at least one is made better off. This holds regardless of whether the redistribution is actually made or not. Hicks is careful to note that the costs of redistribution must be considered in the overall analysis of the efficacy of any change.

This very utilitarian approach holds sway even to this day and is at the heart of traditional cost-benefit analysis. By explicitly separating the positive, i. e., objective, aspects from the normative, i. e., subjective aspects, economists can avoid the need to make interpersonal comparisons of utility and/or judgments on distributional issues - "it is quite impossible to decide on economic grounds what particular pattern of income-distribution maximizes social welfare" - and focus on issues of efficiency.

Arrow (1950), among others, has raised doubts about the value of the Kaldor-Hicks criteria for the purposes of making policy choices and measuring social welfare. Pareto optimality is almost useless for policy as rarely will there be a case where at least one person is not made worse off. Potential Pareto optimality is problematic, as was noted by Hicks, because of the potential for an infinite number of redistributions and therefore an infinite number of outcomes. Also, since other Pareto optimal outputs could be reached if there were an initial redistribution of assets, and these are not considered, the criteria sanctifies the status quo, which in itself implies an ethical choice.

Societal Values Outside of Individual Values Missing Interactions

There are important values that society may hold dear that transcend the individual. These values may be related to issues of equity or they may reflect goods and services that have a more common character, such as culture and particular aspects of nature and nature's services. Klaasen and Opschoor (1991) state that "Society may have values that deviate from (aggregated) individual values, e. g., on the basis of society's much longer life expectancy,

society as a whole may thus value environmental quality more highly than individuals do." Arrow (1950) addresses these when he states that "In general, then, there will be a different ordering of social states according to the direct consumption of the individual and the ordering when the individual adds his general standards of equity (or perhaps his standards of pecuniary emulation). We may refer to the former ordering as reflecting tastes of the individual and the latter as reflecting his values."

Missing Interactions

By estimating economic values at a small scale and then aggregating these, important interactions and interdependencies are lost. In examining the higher-order effects of climate change, Tol (1996) notes that the "cost of impacts together is larger than the sum of the individual impacts." A prime example of this is seen in how agriculture has been dealt with in studies evaluating the effect of climate change. Since agriculture comprises only 1 to 2 percent of GDP in developed countries such as Canada, a complete destruction of Canadian agriculture would only result in a 1 to 2 percent GDP loss in standard measures of the effects of climate change. This ignores, however, the extreme dependence of other sectors of Canadian society on agriculture.

On the basis of society's much longer life expectancy, society as a whole may value environmental quality more highly than individuals do.

Aggregating Values across Time

Global and environmental changes tend not only to be large in spatial scale, but also long in temporal scale, spanning across more than one, if not many, generations. This brings with it the problems of how to estimate future values and how then to aggregate these across generations. Two specific aspects of these problems are changing values and discounting and intergenerational equity.

Changing Values

Estimates of value for future generations are sensitive to assumptions about future biological, societal, economic, and cultural systems. How vulnerable will these societies be? How much and how successfully will they be able to adapt? Perhaps more importantly, how will their values and preferences differ from those of members of the present society.

Tol (1994) shows that, by considering the increased willingness to pay for environmental goods that is assumed to come with projected future increases in income, the value of preventing climate change may be significantly higher than common estimates. Furthermore, while such adjustments account for the rising relative preference of future generations for greater quantities of presently valued environmental goods and services, they do not take into account the possibility that future generations may value the environment differently than we do. Take the example of coastal salt marshes, which are now threatened by rising sea-level. Largely ignored today, except for their amenity value and the provision of wetland habitat, a century ago, diked salt marshes were among some of the most valuable agricultural lands in Canada, providing the hay that fueled horse-drawn society. An 1897 estimate of the economic costs of inundating Canada's salt marshes would have put a much higher price on these impacts than a similar estimate today. Similarly, eastern hardwoods, which were regarded by the professional foresters a century ago as weeds, are now valuable commodities harvested for biomass.

Discounting and Intergenerational Equity

Based upon the assumptions that people are impatient and would rather receive a dollar today than tomorrow (the pure rate of time preference) and that an extra dollar is worth less to a richer person than a poorer person (the declining marginal utility of income), economists often apply a discount rate to future values in order to aggregate these across time. The decision to use discounting and the choice of a discount rate are important because of the sensitivity of calculations of total values and thus policy recommendations that may flow from them. For example, at a 7 percent discount rate (as is commonly used in short-horizon project analysis), impacts of $1 billion 50 years hence have a present value of only $33.9 million; the same impacts 200 years hence have a present value of only $1,300.

By estimating economic values at a small scale and then aggregating these, important interactions and inter-dependencies are lost.

The general notion of discounting is based on the idea of a single long-lived agent able to make rational trade-offs between present and future benefits. This assumption does not hold for the long time horizons involved in many global and environmental changes, which involve decisions about the inter-generation allocation of costs and benefits. Just as aggregation across commodities and across individuals within generations cannot be done independently of ethical judgments about distribution, so the choice of a discount rate with which to aggregate values across time is fundamentally an ethical choice about intergenerational equity. On these and other bases a number of authors have argued that discounting is inappropriate to the evaluation of issues involving long-term global and environmental change.

Conclusions

The weakest part of many global environmental assessments, particularly most Integrated Assessment Models, is in how the value of impacts is represented. Much of this stems from philosophical difficulties in attaching values to goods, services, and other aspects that are not normally valued in the same way as marketed commodities. Others are particularly related to issues of scale that present themselves with the need to do aggregations across commodities, individuals, space, and time.

Many of the problems identified here are not amenable to resolution from the perspective of an “objective” science. There will always remain a normative and subjective element to how they are dealt with, thus allowing for a multiple of possible conventions. As Norgaard (1989) argued concerning attempts to incorporate environmental values in the System of National Accounts, an open exploration of multiple approaches is desirable, from the perspectives of both scientific rigor and intellectual honesty.

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The weakest part of many global environmental assessments, particularly most Integrated Assessment Models, is in how the value of impacts is represented.

Modeling Global Biosphere-Atmosphere Interactions

Elena Shevliakova

Carnegie Mellon University
Pittsburgh, Pennsylvania

Modeling interactions between the atmosphere and biosphere continues to pose a significant difficulty, partly because of the tightly coupled flow of water, energy, and carbon between terrestrial ecosystems and the atmosphere.

Modeling interactions between the atmosphere and biosphere continues to pose a significant difficulty, partly because of the tightly coupled flow of water, energy, and carbon between terrestrial ecosystems and the atmosphere. In recent years the climate-change community has taken a number of different approaches toward understanding physical, ecological and biogeochemical aspects of vegetation-climate interactions. Studies have been performed on different spatial and temporal scales, from an individual leaf to the entire globe (IPCC 1995).

Modeling biosphere-atmosphere interactions on the global scale

Past studies of the global-scale biosphere-atmosphere have been performed in one of two diagnostic ways: (1) impacts of climate change on the biosphere, or (2) biosphere feedbacks to the climate system. Global impacts studies have been performed with biogeography and/or biochemistry models (VEMAP, 1995). Biosphere feedbacks to the climate system have been explored with land-surface models in GCMs. A third, newly emergent approach is the integrated study of biosphere and climate interactions (Foley, et al., 1996).

Biogeography models attempt to simulate global equilibrium distributions of vegetation under current and future climates. Most of these models are correlative in nature and rely on observed associations between climate and vegetation. Most have been developed with a rigid environmental envelope approach in which a few climatic constraints determine the pattern of vegetation cover. More recent models such as BIOME-1 (Prentice, et al. 1992), MAPSS (Neilson, et al., 1992), and BIOME 3.0 (Haxeltine and Prentice, 1996), have combined elements of correlative and mechanistic approaches, but focus primarily on modeling potential vegetation types. Despite recent advances in understanding the factors that control vegetation distribution, existing models are not able to simulate prevalence of different vegetation types equally well.

Biogeochemistry models focus on the simulation of nutrient flows among vegetation, soil and the atmosphere. Typically these models deal only with changes in carbon and nitrogen flows and net primary productivity (NPP) due to climate change. These models assume constant distributions of vegetation and soil types. The VEMAP (1995) study compared the sensitivity of different biogeochemistry models to assumptions about different vegetation distributions, carbon fertilization effects and climate change.

Land-surface models aim to represent the exchange of energy and moisture between the atmosphere and the Earth's surface for prescribed distributions of vegetation and soil. The

joint WGNE-GCIP Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) has considered 22 land-surface models to understand their capabilities and potential applications. At the land surface, the available radiative energy is partitioned into latent and sensible heat fluxes depending on the type of vegetation. The earlier land-surface models used very simple parameterizations for such partitioning. In later models such as the Simple Biosphere (SiB) model of Sellers et al. (1985), the Biosphere-Atmosphere Transfer Scheme (BATS) of Dickinson et al. (1993), and the Land Surface Exchange (LSX) of Pollard and Thompson (1995) plant-soil-atmosphere interactions are explicitly parameterized to represent vegetation physiological processes such as evapotranspiration and seasonal changes in foliage. As a rule, detailed physical descriptions of canopy and soil processes in these models lead to an explosion in the number of parameters and needed computational resources. The latter is of particular concern in long-term climate change simulations.

Typically, the vegetation distribution in land-surface models is assumed to be constant over time. There are two general approaches to describing vegetation at the grid scale of an atmospheric GCM (~ 300 km x 300 km). In the first, more widely used approach (e. g., SiB), the entire area of each grid cell is assumed to be covered by a homogeneous mixture of vegetation. In the second approach of Mosaic LSM, different types of vegetation are assumed to occupy different areas of the cell and to interact independently with the atmosphere (Koster and Suarez, 1992).

Development of global dynamic models of vegetation remains a high priority task in predicting realistic impacts of future climate changes on vegetation.

Development of global dynamic models of vegetation remains a high priority task in predicting realistic impacts of future climate changes on vegetation. Shevliakova discussed the attempts she is aware of to address this issue. These attempts to simulate vegetation dynamics fall under three general strategies. The first strategy, represented by the work of Woodward et al. (1995), aims to model such global vegetation characteristics as Leaf Area Index (LAI), Net Primary Productivity (NPP) and stomatal conductance. These are calculated with a plant productivity and phyto geography model. The second strategy, advanced by Foley et al. (1996), is based on the concept that vegetation system dynamics are shaped to maximize NPP. Thus, for a given climate, a plant functional type (PFT) can be identified which can survive given the local conditions (soil and climatic) and which maximizes NPP. The third strategy is incorporated in the process-based model Hybrid of Friend, et al. (1997). It is based on a stand modeling approach and is able to project spatially, temporally and biologically detailed responses to climate change.

An integrated approach to modeling biosphere-atmosphere interaction was implemented in the Integrated Biosphere Simulator (IBIS) model (Foley, et al., 1996). The first version, IBIS 1.1 consists of four different modules that describe vegetation phenology, biogeochemistry, land-surface-atmosphere interaction, and dynamic changes in specific plant types. A combination of different PFTs provides the vegetation cover. In a manner similar to biogeography models, this model applies a set of climatic constraints to define which PFTs can potentially exist within each grid cell. Then, using the approach of Haxeltine and Prentice (1996) from BIOME 3.0, potential PFTs are ranked according to their NPP and the dominant PFTs are defined to prevail. The information about vegetation structure is used in a land-surface module based on the LSX land-surface model (Pollard and Thompson, 1995). The land surface module simulates fluxes of energy, moisture, momentum and CO_2. The IBIS model can be directly incorporated into a GCM and allows study of atmosphere-biosphere interactions in an internally consistent manner.

Scale and Vegetation Description

The choice of vegetation description is scale dependent. At a smaller scale it is possible to describe vegetation in fine taxonomic details (e. g., species). At a larger scale, description in terms of general physiognomic or environmental features has been often used (e. g., biome). A number of different classification schemes have been proposed (Table 1.31). Until recently, environmental schemes have been frequently used in modeling biosphere-atmosphere interactions. Köppen (1936) developed a bioclimatic classification scheme based on physiological vegetation classification. This scheme depends on mean monthly temperatures and seasonal precipitation expressed through mean annual precipitation. The Köppen scheme distinguishes 12 different bioclimates. Another popular and widely used bioclimatic scheme is the Holdridge Life Zone Classification (1947), based on the three climate parameters: annual biotemperature (ABT), annual potential evapotranspiration (APT), and average total annual precipitation. Annual biotemperature is calculated by averaging only positive temperatures over the course of a year.

The choice of vegetation description is scale dependent

Approach	**Developers**	**Basic Units (disaggregated and aggregated)**	
Physiognomic	Grisebach Kuchler Beard	structural type of growth form (e.g., grass, broad-leaved deciduous tree)	formation biome
Environmental	Koppen Thornthwaite Holdridge	bioclimatic zones	
Many-factor	Passarge Marcus Tuxen	microlandscape or naturecomplex, bio-geocoenose	landscape units
Biotic Areas	Shmid Dice	vegetation girdle~geographic areas of species	biocoenoce-type biotic provinces
Zones and Series	Merriam Kendeigh Braun-Blanquet	ecological series~ordination along env. gradients	belts or zones formation series
Species Dominance	Tansley Chip Wittaker	'association'	
Vegetation Dynamics	Moss Coupland Clements	succession sequence of ecological series	associations climax communities
Numerical	Tuomikoski Goodall Greg-Smith	measurements of relative similarity of species distribution	nodum

Table 1.31

Different vegetation classification approaches

The IPCC impacts study criticized correlative biogeography models for lacking causal relationships between climate and plant physiology, and thus their presumed ability to predict only the current distribution of biomes. In the later mechanistic models such as BIOME 3.0 and IBIS 1.1, the representational sophistication of the vegetation increased further to describe vegetation not in terms of biomes but in terms of plant functional types (PFTs). The notion of PFTs is not completely new in vegetation classification and is related to physiognomic approach (Table 1.31).

The notion of growth form goes back to Waring's "Oecology of Plants" (1909). According to Waring, plant formations (or biome types) are characterized by their physiognomy and structure (e. g., dominant growth forms) and by some environmental characteristics (e. g., location or temperature range). For example, consider different grass formations: grassland (savanna), temperate grassland (steppe), alpine meadows, and salt marshes. All these formations are dominated by the same growth form: grasses and grass-like plants. Some researchers used classifications similar to growth form such as life-form, physiognomic plant types, and PFTs. Many different schemes were developed to classify vegetation formation from the physiognomic point of view, with different kinds and numbers of growth forms and consideration for environmental factors.

The growth-form based approach is the best suited to the analysis of ecosystem impacts and feedbacks to the climate system on the global scale because it provides the means to: 1) explore changes in vegetation structure; 2) reflect on important characteristics of the land surface such as the amount of respiring phytomass (e. g., trees vs. grasses), the amount and configuration of photosynthetic and transpiring surfaces (e. g., needle leave vs. broadleaf), and seasonal variations (e. g., deciduous vs. evergreen); 3) describe only the general characteristic of plants that are essential in modeling atmosphere-biosphere interactions and are computationally efficient.

The growth-form based approach is the best suited to the analysis of ecosystem impacts and feedbacks to the climate system on the global scale.

Analysis of Current Global-Scale Climate-Vegetation Relationships

There is a widespread acknowledgment that climatic factors such as ambient air temperature, incident solar radiation and water availability play an important role in the distribution and functioning of vegetation. These climatic factors are complex and can, therefore, be described by alternate ensembles of variables. Climate factors can be included in a vegetation model in a number of ways. First, they can enter as threshold constraints in phenology modules. Second, they can be external drivers of physiological functions (e. g., photosynthesis and respiration). Third, they can be used as scalars in representing the likelihood of different events in the life of vegetation (e. g., the probability of a disturbance). Fourth, climate variables can be a factor in vegetation classification itself.

A probabilistic approach has been applied to the analysis of relationships between global vegetation and climate (Siegel, et al., 1995a; Shevliakova 1996). This approach is applicable to different types of vegetation characterization and to ensembles of physiologically relevant climate variables. It is also computationally efficient . The probabilistic approach to the analysis of vegetation distribution was originally proposed in the 1960s by Richard Goodall (1970), but had only limited use due to the lack of computational power and large-scale information on climate and vegetation at that time. This approach has been used on a small scale to simulate current and potential future distributions of plant species in central European mountain forests (Kienast, et al. 1996).

In their earlier work, Shevliakova and colleagues found that non-parametric methods provide computationally efficient means to explore highly nonlinear relationships between different sets of climatic variables and different vegetation types. These methods can be easily used with different types of vegetation classifications. Non-parametric density-estimation methods are well understood and have increasingly been used for both univariate and multivariate analysis. Shevliakova and colleagues applied a multivariate non-parametric density estimation approach to estimate the probability density functions of different Olson vegetation types over North America. Table 1.32 shows the fewest-variable combinations that are necessary to achieve an excellent degree of agreement between the predicted and observed distributions for each vegetation type.

Vegetation types are ordered according to the mean value of the latitude at which they occur. The first column shows mean values for latitudes at which each Olson vegetation type occurs. Columns 3 through 11 show the combination of different variables necessary to describe the prevalence of that type. The column titled “other” is included to show that variables other than those used in columns 3 through 11 may be needed to achieve excellence in prediction. For two vegetation types, wooded tundra margin and deserts, no combination of explanatory variables was found to provide excellent agreement between predictions and observations. Table 1.32 shows that in high latitudes, seasonal characteristics such as minimum and maximum temperatures and available moisture during the warm period play an important role. This table also indicates that the required number of variables increases in the area below wooded tundra margin (a proxy for tree-line), where different kinds of forests are currently observed.

	latitude												
Vegetation Type	mean	biot	prcp	ptmax	elv	tmin	wroot	tmax	pmin	pmax	mi	other	number of variables and kappa
polar desert	79.85			*		*							2 (0.88)
tundra	67.14			*		*		*	*				4 (0.91)
wooded tundra	59.93	*	*	*	*	*	*	*	*	*	*	?	? (0.84)
Northern taiga	59.51	*	*	*	*	*		*					6 (0.87)
main boreal conifer forest	57.25	*	*	*	*	*	*						6 (0.87)
Southern taiga	55.92	*	*	*	*		*						5 (0.87)
snowy rainy coastal conifer	55.77	*	*		*								3 (0.87)
wetlands	52.92	*	*	*	*	*	*		*				7 (0.87)
snowy non-boreal conifer forest	49.56	*	*	*	*								4 (0.89)
grass/shrubs	46.24	*	*	*	*								4 (0.90)
deciduous forest	45.38	*	*	*	*								4 (.094)
cool semidesert	40.61	*	*	*	*								4 (0.85)
Scrub/woodlands	34.79	*	*	*	*								4 (0.90)
non-snowy conifer forest	33.37	*	*	*									3 (0.87)
warm semidesert	30.58	*	*	*	*								4 (0.89)
desert	30.56	*	*	*	*	*	*	*	*	*	*	?	? (0.74)
temperate forest	26.22	*	*	*									3 (0.96)
xerophytic woods and savanna	23.28	*	*	*									3 (0.94)
tropical seasonal complexes	15.63	*	*	*									3 (0.99)
tropical forest	15.36	*	*							*			3 (0.99)

Table 1.32

Summary of key variables for describing different vegetation types

Although many models of vegetation distribution have similar principles of plant functioning at their foundation, they choose very different sets of climatic variables to represent these principles or use different methodologies to estimate the variables . For example, consider the representation of cold tolerance of plants. Woodward, in his earlier studies, uses the absolute minimum temperature, obtained by regression of the monthly minima from available meteorological stations. In BIOME 1.0, Prentice and colleagues use the temperature of the coldest month, estimated from the 12 monthly averages from Leemans and Cramer climate database. In the BIOME 3.0 model of Haxeltine and Prentice, thresholds for absolute minimum temperatures are obtained by looking over available data from meteorological stations from Muller database. As Katherine Prentice notes, “Any combination of terms has potential, and yet there is no perfect index from a biological point of view.”

The choice of climate variables is an important part of the specification of the land-cover model. The analysis outlined above is able to provide insights and help in choosing the necessary set of climate variables for adequate representation of climate-vegetation relationships. This choice depends not only on ecophysiological relevance, but also on the availability and accuracy of information (e. g., soil nutrient characteristics are less readily available than soil types). Often it has been known from the small-scale studies (e. g., individual plants or communities) that variables such as vapor-pressure deficit, photosynthetically active radiation (PAR), snowpack, and wind speed are important factors in plant functioning, but information about these variables is not available on a global scale. In such cases it may be feasible to use the information from the 1xCO2 equilibrium simulations by different GCMs.

Non-parametric methods provide computationally efficient means to explore highly nonlinear relationships between different sets of climatic variables and different vegetation types.

Aggregation of processes in individual tree models: a Case Study of TREGRO

In global vegetation models (e. g., IBIS, Hybrid) different types of vegetation compete for resources. Their growth and development are simulated through modeling carbon accumulation in different compartments: leaves, branches, stems, and roots. Representation of carbon accumulation and partitioning in global vegetation dynamics models is similar to individual plant models (e. g., TREGRO of Weinstein, et al., 1991), but individual plant models have more plant compartments, finer temporal resolution and are parameterized for a particular species. Parameter estimation for the individual plant models has been facilitated through a sustained effort in data gathering on tree responses to the prevailing environment and imposed stresses.

In order to understand the increased sophistication and complexity of individual plant models, sensitivity and uncertainty analyses must be performed. Siegel et al. (1995b) performed such analyses for the TREGRO model and explore effect compartment and temporal aggregation on the model’s predictions. Model reduction techniques have been used in different fields such as chemical engineering, economics and ecology. Reduced form models offer computational efficiency and often require specification of fewer input parameters. The disadvantage of reduced form models is that they may be less accurate, and be unable to fully reproduce the behavior of the parent model. Because the accuracy and reliability of the simplified model depends upon the simplifying assumptions employed, model reduction can be viewed as a sensitivity study of model predictions to the nature of the simplifying assumptions.

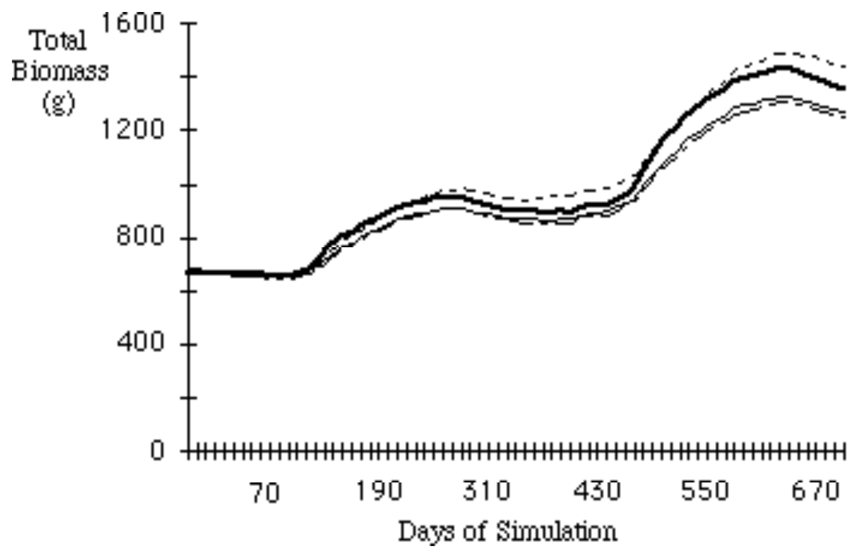
In the case study of TREGRO, simulations and analyses were performed for a red spruce tree using meteorological data collected near Ithaca, New York. In the full TREGRO model, a red spruce tree is represented by 12 compartments (i. e., branch, stem, 4 leaf (needle) age classes, and coarse and fine root classes in 3 soil layers). Carbon stored in each of these compartments

is divided into three types: living structure; dead structure or wood; and total non-structural carbon (TNC). The total carbon balance in a plant is calculated on a daily time step. The key to time aggregation is estimation of photosynthesis for time steps greater than one hour. All other parameters in TREGRO are calculated on a daily time step.

In order to explore the sensitivity of model predictions to uncertainty in the empirical model parameters, a subset of 40 parameters was treated probabilistically: respiration and growth rates for different compartments, ozone stress-related modifiers, fractions of leaves of each class in shade and sun through the course of a day, and initial masses of tissues in the compartments. The probability distributions and interrelationships for these parameters are subjective judgments of the model developers. The relationships between inputs and outputs were examined through partial rank correlation analysis.

Model reduction can be viewed as a sensitivity study of model predictions to the nature of the simplifying assumptions.

The case study results indicate that the most compact model is over an order of magnitude faster than the full TREGRO model. When using a time aggregated TREGRO, leaf TNC and biomass typically provide better results than the woody parts. When both time aggregation and compartment aggregation are employed the total biomass results are closer to the full TREGRO results (see Figure 1.33). This increase in computational efficiency is achieved at a small loss in accuracy of total biomass predictions. However, simulations of TNC in the aggregated versions of TREGRO are different from TNC values in the full version of the model. This suggests that this model reduction approach may be suitable for use in analyses where accurate TNC results are not needed.



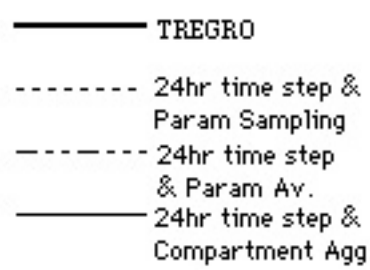


Figure 1.33
Comparison of the mean values of total tree biomass from the full version of TREGRO (12 compartment, hourly time step) and three versions of μ-TREGRO (24 hr time step, compartments and environmental inputs aggregation). In all four cases, the means were derived from 100 simulations with different combinations of 40 parameters describing physiological and growth processes.

This case study of the individual plant growth model TREGRO provides insight into the key factors controlling the simulated dynamics, and guides the development of an acceptable reduced form model in which longer time steps and fewer compartments are used in the simulation. The development of such reduced form models offers computational efficiency gains and requires fewer parameters for larger scale models. Analysis of model uncertainties with different compartment and time step aggregation are needed both to permit quantification of the impact of the myriad uncertainties in model inputs, empirical parameters and underlying structure, and also to guide future model development on different scales.

The most compact model is over an order of magnitude faster than the full TREGRO model.

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The development of such reduced form models offers computational efficiency gains and requires fewer parameters for larger scale models.

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Cloud-Radiation Parameterizations as a Scaling Problem

Richard C. J. Somerville

Scripps Institution of Oceanography
University of California, San Diego

In modeling the global climate, scaling is an especially critical issue, because small-scale processes, such as the formation of clouds and the role of clouds in the transfer of both solar and terrestrial radiation, have important effects on the climate system. Clouds are much too small to be modeled explicitly in a global simulation, and the physical processes involved in clouds are still imperfectly understood, but clouds and their radiative effects are too important to be ignored. The typical solution is to parameterize these effects. In this context, a parameterization is a rule or algorithm for representing the statistical effects of an ensemble of small-scale processes on the large-scale climate, with the understanding that these effects must be able to be prescribed explicitly as a function of conventional large-scale climate variables, such as wind, temperature and humidity.

Cloud-radiation interactions and feedbacks are at the top of every recent list of high-priority research topics in climate modeling because they dominate the response of climate models to imposed forcings.

Climate models are solved numerically on global grids with a typical resolution of a few hundred kilometers horizontally and about one kilometer or less vertically. When the model values of climate variables at this resolution are used to prescribe clouds, the resulting rules are often highly simplistic. These parameterizations may have some intuitive appeal, but they are rarely justifiable theoretically and have almost never been tested empirically in any thorough and satisfying way. For example, a typical parameterization might make the cloud amount in a model grid volume proportional to some simple function of the excess relative humidity above some prescribed threshold critical value. Both the functional form and the critical value can be "tuned" to reproduce crude observed climatic properties, such as the global planetary reflectivity, which is mainly due to clouds. However, parameterizations of this sort need not bear any resemblance to the way clouds actually vary in space and time in the present atmosphere, let alone as to how they will change and feed back on any future climate which differs from the present one. To put these highly idealized parameterizations on a firmer footing, a major direction in current research is to test them against observations.

It is important to realize that cloud-radiation interactions and feedbacks are not simply fascinating but ultimately unimportant playthings of climate modelers. On the contrary, they are at the top of every recent list of high-priority research topics in climate modeling, for the compelling reason that they dominate the response of climate models to imposed forcings such as changes in the atmospheric carbon dioxide concentration. Until a much better understanding of cloud-radiation processes is obtained and incorporated in models, it is a simple fact that large uncertainties will necessarily characterize all model predictions of climate change. Thus, the climate modeling community has been driven by the results of its own research to the realization that there is now a crucial need for careful comparisons between products of model cloud algorithms and observations of cloud-radiation processes in the actual atmosphere.

Somerville and colleagues have used an atmospheric general circulation model, or GCM, typical of those at the heart of contemporary climate modeling efforts, in inverse climate change simulations to study how climate sensitivity is affected by different cloud-radiation parameterizations. They have also used observations from several field programs to begin to test these same parameterizations for realism. In addition to a relative-humidity-based cloud scheme, of the type outlined above, they have tested several types of parameterizations incorporating prognostic cloud water, both with and without interactive cloud radiative properties. Their inverse climate change simulations involve forcing the model by prescribed global changes in sea surface temperature. Such simulations are far less ambitious than attempts to mimic the way the climate will be affected by gradual changes in greenhouse gas concentrations, but they are much easier to interpret and can thus be highly insightful.

Two plausible approaches to parameterization give feedbacks of opposite sign in terms of the cloud contributions to planetary reflectivity.

In their GCM, the increase in cloud water content in a warmer climate leads to optically thicker middle and low clouds and in turn to negative shortwave feedbacks for the interactive radiative schemes, while the decrease in cloud amount produces a positive shortwave feedback for the schemes with specified cloud water path. Put in everyday terms, this means that in a warmer climate, clouds contain more water and are thus more reflective and tend to act like a thermostat to reduce the warming, according to the parameterizations tested that include varying water amounts and cloud radiative properties which depend on cloud water content. However, when the parameterizations were altered so that they did not include varying water amounts, the clouds simply decreased in amount in the warmer climate, thus decreasing their role in reflecting sunlight, and thereby amplifying the warming. In short, two plausible approaches to parameterization give feedbacks of opposite sign in terms of the cloud contributions to planetary reflectivity.

A similar dilemma occurs in considering the cloud effects on the transfer through the atmosphere of infrared radiation emitted by the Earth. This is essentially the cloud contribution to the greenhouse effect. For these so-called longwave feedbacks, the decrease in high effective cloudiness for the schemes without interactive radiative properties leads to a negative feedback, while for the other parameterizations, the longwave feedback is positive. In other words, cirrus clouds, which are important contributors to the natural greenhouse effect, change with a climate warming so as to occupy a smaller fraction of the sky in the warmer climate than they do today, thus opposing the warming, according to the tested parameterizations of clouds without varying water. However, when the cloud water content is allowed to vary, the higher water content in the warmer climate adds to the greenhouse effect by making the clouds more opaque to infrared radiation, thereby amplifying the warming.

Thus, as in the case of cloud effects on solar radiation, two classes of parameterization give feedbacks of opposite sign in computing how clouds affect the transfer of terrestrial radiation through the atmosphere. Furthermore, in each class of parameterization, the sign of the feedback is different for solar radiation than for terrestrial radiation. It is also important to keep in mind that the quoted GCM results are all for global average circumstances. The global averaging obscures potentially serious local differences in sensitivity to clouds and cloud feedbacks. Whether a given region of the world experiences a positive or negative net cloud-climate feedback will depend on the types of clouds present there, which will certainly vary, not only from place to place, but with season, synoptic meteorological regime, and many other factors. Modeling of regional climate variability is still in its infancy. These sensitivity studies demonstrate how crucial it is that observational evidence be brought to bear to determine which, if any, of the tested parameterizations realistically represents how clouds behave in the actual atmosphere. Only recently have appropriate observations and theoretical tools begun to be available to tackle this task (Lee et al., 1997).

Somerville and colleagues' comparisons with observations are made using a theoretical diagnostic tool which they refer to as a single-column model, or SCM (see Figure 1.34). The model output includes temperature and moisture profiles, clouds and their radiative properties, diabatic heating terms, surface energy balance components, and hydrologic cycle elements. These comparisons of model versus measurement demonstrate clearly that it is inadequate to treat cloud amount as a simple function of relative humidity and to regard cloud optical properties as prescribed. Instead, the more realistic schemes are the more physically complete ones, i. e., those with explicit cloud water budgets, comprehensive treatments of cloud micro physics and interactive radiative properties which are based on the calculated cloud water amounts and detailed microphysics.

The fundamental concept of their SCM is to force and constrain an isolated time-dependent atmospheric GCM column with estimates of observed advective flux convergences, by which they mean the rates at which the wind advects heat, momentum and moisture into the column. These flux converges can be estimated accurately from modern measurements. The critical step is then to compare the model output with observations to judge the realism of the parameterizations. Because the SCM has only one space dimension (vertical), it is computationally very fast, and so it is practical to explore large ranges of all the relevant parameters by making hundreds or even thousands of numerical integrations, which is impossible with a full three-dimensional GCM.

These comparisons of model versus measurement demonstrate clearly that it is inadequate to treat cloud amount as a simple function of relative humidity and to regard cloud optical properties as prescribed.

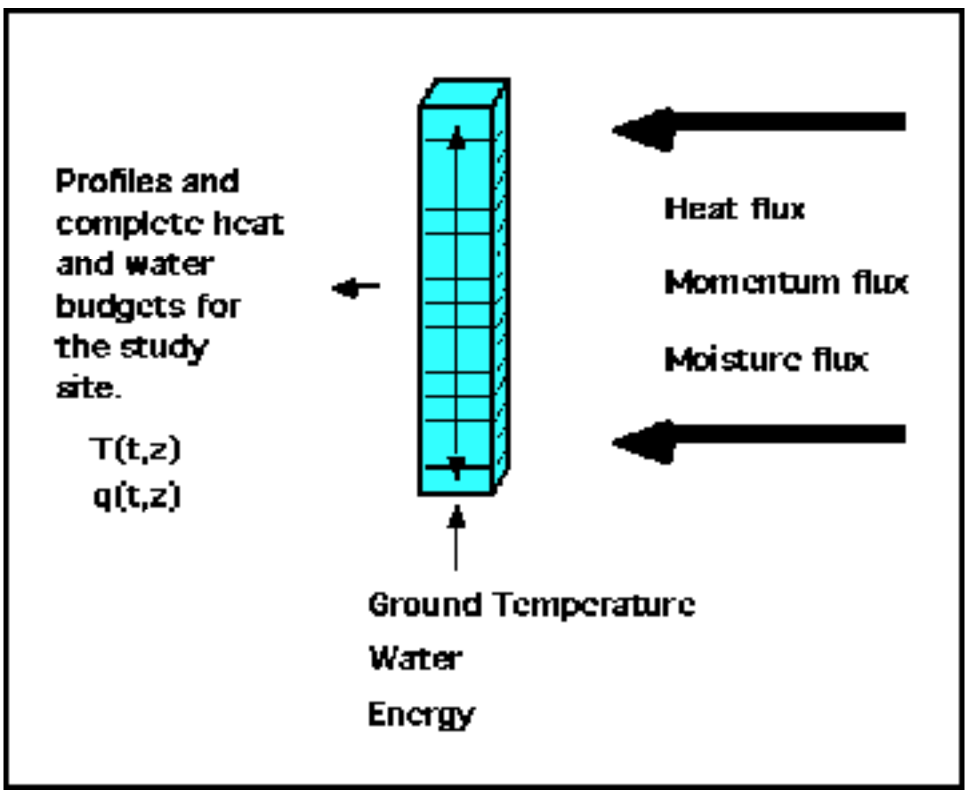

Figure 1.34

Diagram of a single column model

Their SCM contains switch-selectable parameterizations based on current GCM practice. Their approach involves validating parameterizations directly against measurements from field programs, and then using this validation to tune existing parameterizations and to guide the development of new ones. They use the SCM to make the scaling link between observations and parameterizations. Surface and satellite measurements are used to provide an initial evaluation of the performance of the different parameterizations. The results of this evaluation are then used to develop improved cloud-radiation and precipitation schemes, and these schemes can then be tested in GCM experiments.

The SCM is diagnostic rather than prognostic. Its input is an initial state, plus the time-dependent advection terms in the conservation equations, provided from measurements at all model layers. Its output is a complete heat and water budget for the study site, specified as a function of altitude and time. The SCM thus may be thought of as a way of asking the parameterization in question how it would behave if it were forced and constrained by the fluxes that are actually observed at a given site in nature, rather than the fluxes that a GCM might compute under artificial circumstances.

The single column model is used to make the scaling link between observations and parameterizations.

In the hierarchy of climate models, this diagnostic model is intermediate between a physically comprehensive, fully three-dimensional model and an idealized treatment of an isolated physical process. Somerville and colleagues' recent research includes the following elements: incorporation of model improvements, particularly in the cloud-radiation formulations; testing and validation of the model through diagnostic analyses of observational data sets; and use of the diagnostic model to interpret the results of multi-dimensional models (i. e., GCMs), and to determine the sensitivity of model results to alternative parameterizations of physical processes.

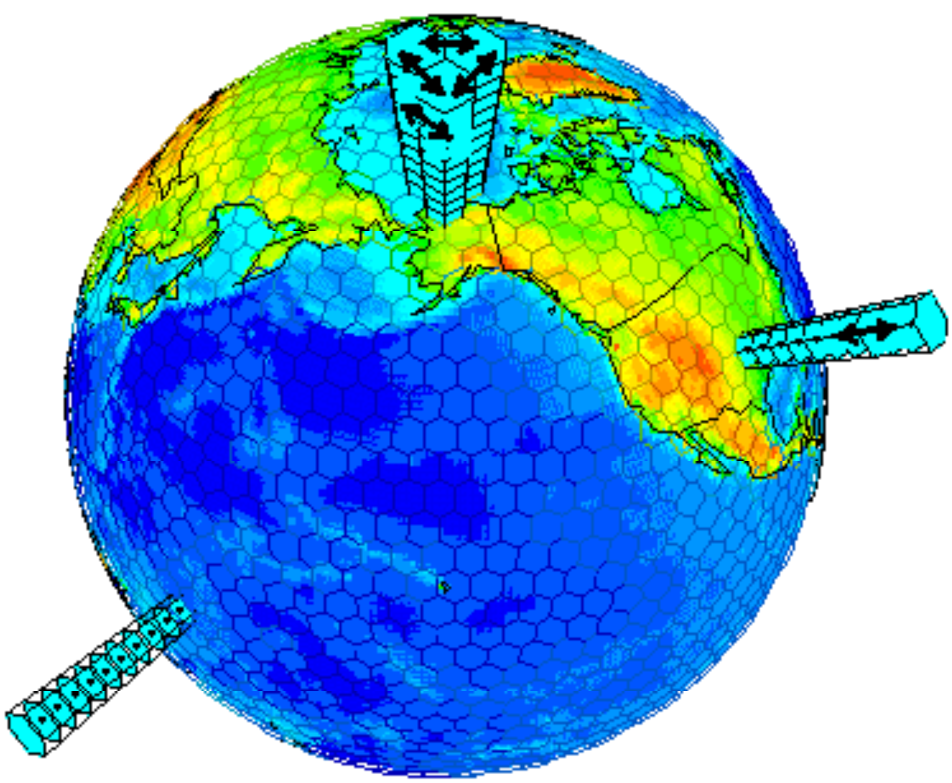

Figure 1.35
The SCM applied at three ARM sites: the Southern Great Plains, North Slope of Alaska, and Tropical Western Pacific sites.

Because the essence of the diagnostic use of single-column models involves comparing warming model output with intensive observations of an atmospheric volume representative of a single GCM grid cell, this type of research could not have been undertaken until modern observational technology was developed and deployed at appropriate sites. Suitable recent observations from field programs such as the Atmospheric Radiation Measurement program (ARM) of the U. S. Department of Energy are now available and give researchers the large data sets they require (see Figure 1.35). These observations provide invaluable information for the development of improved parameterizations. Such measurements permit the validation of GCM parameterizations using actual physical conditions rather than hypothetical ones. Independent measurements of quantities such as precipitation and net surface solar irradiance provide sensitive tests of the realism of parameterizations. In brief, this methodology allows direct observational validation of physical process parameterizations (e. g., Randall et al., 1996).

Somerville and co-workers continue to develop and directly validate improved parameterizations of cloud-radiation and precipitation processes, using a diagnostic SCM together with observational data. It is now well-recognized, in both the GCM and numerical weather prediction (NWP) communities, that SCMs are useful tools for testing and improving parameterizations by validating them empirically against field observations. Their group has recently begun to emphasize precipitation as a crucial validation parameter. The extension to precipitation algorithms is a relatively new thrust, which should help accelerate progress with the cloud-radiation algorithms, because of the close connection via cloud microphysics. In one sense, precipitation is simply an additional validation route for the work on cloud microphysics. At the same time, improvements in the cloud water budget calculation can not only benefit the radiation schemes through improved specification of cloud radiative properties, but can also lead to improved precipitation simulations.

Sensitivity studies demonstrate how crucial it is that observational evidence be brought to bear to determine which, if any, of the tested parameterizations realistically represents how clouds behave in the actual atmosphere.

They are currently concentrating on improved physical process parameterizations for the treatment of summer convective precipitation and cloudiness. The proposed work combines analysis of observational data, theoretical process studies, diagnostic modeling, and GCM experimentation (Lee and Somerville, 1996). Their principal geographical regions of interest are mid-continent North America, where the main ARM sites in Oklahoma and Kansas are located, and the western tropical Pacific, which was the scene of the TOGA-COARE (Tropical Ocean Global Atmosphere Combined Ocean Atmosphere Response Experiment) field program and will also be an ARM site. They are pursuing a three-track strategy: (1) utilize stochastic radiative transfer theory (Malvagi et al., 1993; Byrne et al., 1996) to develop improved parametric representations of cloud-radiation interactions for atmospheric models; (2) validate and improve these parameterizations by using single-column models (Iacobellis and Somerville, 1991a, b; Randall et al., 1996) to make direct diagnostic comparisons with field observations; (3) test the parameterizations in their GCM to determine the sensitivity of model results to all aspects of the physical parameterizations (Lee et al., 1997).

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SCMs are useful tools for testing and improving parameterizations by validating them empirically against field observations.

Cross-Level Inference in Political Science

Detlef F. Sprinz

Potsdam Institute for Climate Impact Research
Potsdam, Germany

The Problem of Cross-Level Inference

Social scientists have a long tradition in modeling across various levels of analysis or levels of aggregation. While economists often distinguish microeconomics (e. g., the study of individual firms, individual consumers, etc.) and macroeconomics (e. g., whole economies as part of the world economy), sociologists distinguish, inter alia, individuals, groups and states. Similarly, political scientists, especially specialists in international relations, may focus on at least three levels of analysis such as the individual decision-maker, country aggregates (e. g., country positions in international environmental negotiations), and the international system of countries (e. g., the occurrence of international war on the global level). However, the relationships across the various levels of analysis do not necessarily receive adequate attention, in particular if findings at lower levels of aggregation hold or do not hold at a higher level of aggregation. Furthermore, researchers are often interested in micro-level relationships but only have aggregate data at hand. The problem of cross-level inference deals with both types of problems: relating findings at lower levels of aggregation to higher levels of analysis and suggesting ways to recover individual-level relationships when only aggregate-level data are available.

The problem of cross-level inference deals with relating findings at lower levels of aggregation to higher levels of analysis and suggesting ways to recover individual-level relationships when only aggregate-level data are available.

Most of the literature in the social sciences seems to be influenced by the research findings of William Robinson in 1950 who showed that states with more foreign-born residents tended to have more residents literate in English. A scholar using only aggregate data would have concluded that the foreign-born were unusually literate in English. However, the individual-level census data showed just the reverse was true: foreign-born residents were less literate in English than native-born Americans. Thus even the sign of the aggregate-level relationship was wrong. Robinson concluded that we should avoid using aggregate-level correlations to draw conclusions about otherwise unobservable individual-level relationships; he called this the "fallacy of ecological correlation."

Since data from both levels of analysis are available, the problem could fortunately be resolved: In this specific case, the ecological fallacy occurs because particularly strong groups of foreign-born persons were clustering in the same geographical units with highly literate groups of persons, and while the individual-level relationship between being foreign-born and literacy is negative, the clustering of foreign-born groups with highly literate persons in cities resulted in an positive aggregate-level relationship. However, detection of the error in inference rests on the additional information available from individual level data - which do not always exist.

Examples of Aggregation Bias

Students of comparative politics have been advancing the various merits of different election schemes for decades, e. g., the simple majority rule versus proportional representation for allocating Parliamentary seats, as well as single versus multiple member districts. Not intending to review this discussion, in the following, Sprinz simply demonstrates the aggregation bias introduced by relative majority electoral laws as compared to proportional representation.

The recent British Parliamentary elections were held on the basis of single-member districts, i. e., the candidate receiving the relative majority of votes will represent his or her voting district in the House of Commons (see Table 1.36).

Aggregation bias is introduced by relative majority electoral laws as compared to proportional representation.

	Party	% Votes	Seats	% Actual Seats	% Points Bias (Seats)
Government Party	Labor Party	45%	419	67%	+22%
Opposition Parties	Conservatives Party (Tories)	31%	165	26%	-5%
	Liberal Democrats	17%	17	3%	-14%
	Other	7%	29	5%	-2%
Total		100%	630	100%	0%
% Government		45%		67%	+22%
% Opposition		55%		33%	-22%

Table 1.36

Results of recent British Parliamentary Elections.

Data Source: www.bbc.co.uk/election97/live/index.htm

Note: Figures may not add up due to rounding.

The table contrasts the actual percentage of seats received in Parliament with those based on proportional representation. For example, with 45 percent of the popular vote, the British Labour party received two-thirds of the seats in Parliament. In order to easily detect the degree of bias (in percentage points), Table 1.36 computes the absolute difference between the percentage of seats expected by way of proportional representation as opposed to the actual percentage of seats allocated by way of a relative majority system (plurality). The results show that the governing party has benefited substantially from the single member, relative majority electoral system as opposed to proportional representation laws. In fact, from the perspective of proportional representation laws, the opposition parties have “won” the election!

While such aggregate results from election outcomes are well-known to comparative political scientists, they also have implications for cross-level inference. National governments negotiate international environmental agreements and implement them by way of domestic laws. Since we often find sufficient differences in the preferences of national governments to negotiate such agreements, the aggregation bias introduced by electoral laws may be quite relevant: National policies may lead to international obligations which lack parallel support at the level of voting districts or even the country at large - which may generate serious problems at the stage of complying with the provisions of international environmental agreements.

An Overview of Major Approaches to Cross-Level Inference

As James S. Coleman reminds us, a first observation is that good social history makes the transitions between micro and macro levels successfully. Sociologists and political scientists have advanced the use of so-called hierarchical (linear) statistical modeling techniques which allow for nesting across levels of analysis. The general concept is that the behavior of individuals is influenced by the social contexts to which they belong and that the properties of a social group are influenced by the individuals who make up that group.

This allows, for example, individual voting behavior to be explained not only by individual-level variables, but also by variables operating at a higher level of aggregation, such as the macroeconomic variables at the level of the voting district (e. g., rates of unemployment or growth rate of the gross regional product). When voting data are made available only at the district level, this grouping of the individual-level data may lead to problems in the estimation procedure because, e. g., the borders of voting districts may be drawn on partisan grounds. As a result, the vector of independent variables may now be correlated with the error term at the aggregate level - leading to a violation of regression assumptions which is not present at the individual level. In essence, model estimation becomes possible as error terms are carefully modeled across levels of analysis in order to avoid violation of statistical estimation procedures. As Langbein and Lichtman eloquently summarize:

> Aggregate models used in lieu of individual data may be comprised both of variables which are theoretically relevant at the individual level and of variables which are added in order to remove the bias by grouping, i. e., variables that reflect the grouping process itself. (Langbein and Lichtman, 1978, 11)

Due to aggregation bias, national policies may lead to international obligations which lack parallel support at the level of voting districts or even the country at large, generating compliance problems.

Since the 1950s, two methods of cross-level inference have been advanced to make inferences on the (normally unobserved) individual level from (observed) aggregate level data: the "method of bounds" and Goodman "ecological regression." In essence, the "method of bounds" rests on accounting identities. Regrettably, this method often does not generate sufficiently narrow intervals for the proportions under consideration to yield interesting results by themselves, and they cannot be statistically estimated due to underidentification problems (more unknowns than equations).

The latter drawback has attracted many researchers to Goodman "ecological regression ," which overcomes the problem of underidentification with the help of strict assumptions. While this allows conventional regression models to estimate the parameters, there is a major practical drawback: Parameter estimates often fall out of the logically permissible range, namely below 0 and above 1! As Achen and Shively suggest from a review of voter transition studies:

> Logically impossible estimates in ecological regression are not flukes. They are encountered perhaps half the time, and more often as the statistical fit improves. Ecological regression fails, not occasionally, but chronically. (Achen and Shively 1995, 75).

More recently, King (1997) has devised a way to fruitfully combine the deterministic results from the method of bounds with statistical estimation techniques in order to overcome the problems posed by the two methods of ecological inference introduced above. His method of ecological inference has been verified with the help of examples where individual-level data are known. Using information from the deterministic method of bounds in combination with advanced statistical methods may generate plausible (and in the case of available individual-level data) verifiable results for the quantities of interest.

In its simplest version, ecological inference seeks to fill the cells of a two-by-two table (or more elaborate tables) when only the marginals are known. However, since the summation of cells (either horizontally or vertically) generates the marginals (either as counts or proportions), it is the same unit of analysis which is involved within a geographic unit, both in the cells or the margins. Thus, ecological inference undoubtedly seeks to yield important substantive insights by filling cells left previously empty, but it does not generate results at a lower unit of analysis (or aggregation). In King's solution, it even "borrows strength" from the bivariate distribution which is estimated across voting districts - thereby creatively using information outside the original domain of primary interest. Thus, there might be an important difference with many of the natural sciences where downscaling refers to using information available at higher levels of geographic aggregation to create representations of data at smaller geographic units.

The Effectiveness of International Environmental Regimes: A Multiple Level Measurement Concept

Ecological inference undoubtedly seeks to yield important substantive insights by filling cells left previously empty, but it does not generate results at a lower unit of analysis (or aggregation).

Although cross-level modeling is challenging, it also enables the development of new concepts. Following the pioneering work by Putnam (1988), which relates the positions taken by governments in international negotiations to properties on the subnational level (e. g., influential interest groups, the electorate, etc.), scholars have developed two-level game-theoretical models to formalize these relationships across levels of analysis in order to deduce new hypotheses. For example, Wolinsky (1994) develops a sequential, two-level game which relates governmental policies on signing international environmental agreements to electoral control; i. e., the electorate takes cues from a government's decision to sign or abstain from international environmental agreements in order to conclude if they are presently ruled by an effective or ineffective government. Other scholars have advanced the notion of the domestic prerequisites for international environmental negotiations or suggested a domestic-level argument about characteristics which induce countries to strive for international environmental agreements (e. g. , Sprinz and Vaahtoranta, 1994).

Perhaps the most intuitive link between domestic political properties and international environmental performance can be demonstrated with the help of a concept for measuring the effectiveness of international environmental regimes. In effect, this measurement concept avoids the problems posed by aggregation bias, and since its most interesting result is on the aggregate level (namely the degree of regime effectiveness), it does not face problems posed by the ecological fallacy. In the following, the concept for the case of transboundary pollution problems is briefly presented and illustrated with select findings from a research project on long-range transboundary air pollution in Europe - an environmental problem which has been regulated under the auspices of the United Nations Economic Commission for Europe.

Underlying the concept of the effectiveness of international regimes presented here is a cost-benefit calculus generally found in environmental economics which has also been applied to political science. The central assumption is that some unitary actor (such as a federal government) is determining the level of effort to protect the environment based on the profitability to its own country ("non-cooperative or counterfactual solution"). In the presence of negative externalities (such as transboundary pollution), environmental damages created outside the jurisdiction are neglected (e. g., lake acidification in Norway is partially caused by air pollution emissions in the UK), and result in transboundary environmental problems. For the group of all countries, this is unlikely to be the optimal solution, since some reciprocal emission reductions may benefit some or even all countries. However, for international environmental cooperation to emerge, some weight must be given to the damages created abroad by polluting

activities taking place within one's own jurisdiction ("cooperative or collectively optimal solution"). Under any circumstances, any rational actor will normally choose an "actual policy" between the non-cooperative solution (minimum) and the cooperative solution (maximum), and the relative positioning of the actual policy in between the minimum and maximum represents the score of international regime effectiveness.

The empirical derivation of the results requires the following modules:

* a transboundary pollution matrix,
* knowledge of economic abatement costs, and
* knowledge of economic damage costs.

In the case of transboundary air pollution in Europe, data of sufficient quality and precision are available for the first two categories, whereas the economic damage costs remain unknown. Therefore, the economic damage cost function has been replaced by a political damage cost function which takes into account the power of domestic political actors, the salience of the topic, and the degree to which a country faces the specific environmental problem (i. e. , an indicator of the distance between the current ecological vulnerability and when this value approaches zero). The calculus employed permits the derivation of country-level results as well as an aggregate results. For reasons of presentation, only the results for three countries are shown for the Helsinki Sulfur Protocol (which mandated a 30 percent reduction of sulfur emissions for signatories between 1980 and 1993) (see Table 1.37).

For international environmental cooperation to emerge, some weight must be given to the damages created abroad by polluting activities taking place within one's own jurisdiction.

The results indicate that the group of all countries substantially exceeds the non-cooperative solution and falls far short of the cooperative solution, however, the international environmental treaty regime does have effects on countries. In some cases, the cooperative solution prescribes a lower emission reduction than for the non-cooperative solution. This applies especially to countries who already undertake high emission reduction policies in the non-cooperative solution, and given the cooperative solution of other countries, their cooperative emission reduction is lower than their non-cooperative solution (e. g., Norway, in Table 1.37). In such cases, the score "1*" was awarded if a country did not fall below the (higher) non-cooperative solution for its actual policy.

The Effectiveness of the LRTAP-Regime (select results)

Results for Sulfur				
Countries	**Belgium**	**Finland**	**Norway**	**All Countires**
Non-cooperative reductions (%)	60	60	70	41
Actual reductions (%)	64	79	74	49
Cooperative reductions (%)	76	64	70	62
Effectiveness Score (%)	0.28	1*	1*	0.39

Table 1.37

Notes: Reductions are expressed in percentage for the periods 1980-93. Those countries where actual reductions are higher than the cooperative reductions have been assigned the score 1*, indicating that they have done more than would have been required in the optimal cooperative solution. The results for "all countries" are based on the weighted average of all countries within the relevant airshed not just the results for the select countries shown here. Source: Sprinz and Helm (1996).

The aggregate-level results show that the effectiveness score is substantially larger than zero and clearly lower than 1. This suggests that (macro) international regimes are not able to carry countries away from their (micro) domestic political basis which constrains domestic and international environmental policy; however, the regime has some discernible effect which should not be underestimated in the empirical domain presented here.

Conclusions

Sprinz provided a brief overview of aggregation and disaggregation problems encountered by political scientists and the major methods used to solve such problems. In addition, the multi-level measurement concept of the effectiveness of international environmental regimes was introduced. While this summary may be comforting to the reader, advances in carefully disaggregating data would be of major interest to students of international environmental policy and politicians alike. In particular, it would be helpful to develop gridded maps of the likely capability of regions to implement international environmental agreements and to use these results in negotiating international environmental agreements. While agreeing on such a map may be politically contentious and will be hard to realize internationally, it would more realistically examine the potential for protecting the international environment .

The group of all countries substantially exceeds the non-cooperative solution and falls far short of the cooperative solution.

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Advances in carefully disaggregating data would be of major interest to students of international environmental policy and politicians alike.

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The Rhetorics of Scale: What's So Global About Global Change?

Marvin Waterstone

University of Arizona
Tucson, Arizona

Waterstone begins with the assumption that our interest in global change includes a policy perspective, and is not simply an effort to achieve a better understanding of Earth systems. He then asserts that better scientific understanding may not necessarily lead to better policies because certain issues may be transcientific, i. e., from a policy perspective, we may have as much scientific information as we need, and the resolution of the outstanding issues may rest primarily on issues beyond science, such as political will.

From a policy perspective, we may have as much scientific information as we need, and the resolution of the outstanding issues may rest primarily on issues beyond science, such as political will.

Science as Constructed Knowledge

Declaring that science is "constructed knowledge," Waterstone asks: How is it that one perspective becomes dominant? How do we interpret phenomena and how do we validate interpretations? There is a need, he says, to be explicit about the criteria we choose in adopting certain views over others and selecting one as the dominant discourse. This is related to issues of power; naming is taming, claiming, and in the case of global change, blaming.

The power of science comes from equating knowledge with truth. The truth claims of science are tied to its methodology. There is a public perception that scientists use prescribed empirical methods which are not subject to their own personal biographies or other factors. Science therefore represents itself through its procedures, presenting truth and methodological rigor as synonymous. Truth claims of science are also tied to the adequacy of scientific explanations, i. e., predictability and control of processes or phenomena. Therefore, science must be seen as immune from social and historical contexts. Further, only those inducted into the scientific community, by virtue of training and credentials, are competent to speak or offer legitimate critiques of science. The genius of science lies in the notion that truth is a set of descriptions of the world based on something we can only imply, not observe (e.g., the atom). The perception is created that science gives us "truth," as opposed to one and only one interpretation of nature.

The "Global" Construction of the Climate Change Problem

Are we all in this together? Who is the "we?" And what is the "this?" How are people differentially implicated in the causes and consequences of climate change? Who gains and who loses from the "we're all in this together" perspective? Those who have contributed most heavily to the problem in the past stand to gain from the notion that we must all contribute to the solution; the developed countries are thus absolved from some of their responsibility and can share the blame and burden of fixing the problem with the developing countries. The "we're all in it together" construction also sets up a moral imperative to do something about it, and to address the transgenerational issues. Thus, Waterstone contends that "global change" is a

construct that serves some interests' purposes and that there are alternative constructs that would serve other interests.

What is lost, he says, are the difficult politics around this issue which get glossed over by the "we're all in it together" construction. If we accept the idea that the causal mechanisms and consequences are homogeneous, global or ubiquitous, that implies a stake for everyone, but this may not be so, or the stakes may be very different.

Not everyone subscribes to the construction of global scale environmental change. It is important to recognize the ways different material positions affect politics and the dominant construction of the problem as global. As an example of how differentiated some of the politics are, Waterstone presents a series of excerpts from a United Nations Special Session on the implementation of recommendations from the 1992 UN Conference on Environment and Development (UNCED) in Rio de Janeiro.

How are people differentially implicated in the causes and consequences of climate change? Who gains and who loses from the "we're all in this together" perspective?

> Tariq Aziz, Deputy Prime Minister of Iraq: Five years after the Rio conference, no substantial steps have been taken to reach goals which it established. On the contrary, attempts are being taken to marginalize and isolate developing countries through various modalities, such as depriving them of their resources, obstructing their scientific and technological development and withholding environmentally clean technology. Certain developed countries are reluctant to fulfill their obligations and resort to coercive economic measures as a means of political intimidation.
>
> Ljerka Mintas-Hodak, Deputy Prime Minister of Croatia: Some 85 percent of the pollution which threatens Croatia's soils and forests ... come from external sources. Regionalization is an important method of implementing Agenda 21 because it addresses problems unique to each region.
>
> Elfatih Mohamed Ahmed Erwa, of Sudan: Developed States continue to increase their production of carbon dioxide. They have not transferred environmentally-friendly technology and [have] used environmental pretexts to keep their markets closed to developing countries' exports. African States are being forgotten and marginalized.
>
> Ail Bin Said Al-Khayareen, Minister of Agriculture, Qatar: The international community should pay special attention to those affected by the implementation of measures to reduce emissions of greenhouse gases, and to those developing countries that are highly dependent on income generated from the production, processing and export of oil ... Developed countries should shoulder their historic responsibilities by honoring their financial commitments.
>
> Bill Clinton, President of the United States: We humans are changing the global climate. ... No nation can escape this danger or evade its responsibility to confront it. We must all do our part - industrial nations that emit the largest quantities of greenhouse gases, and developing nations whose emissions are growing rapidly. Here in the Untied States, we must do better. ... In order to do our part, we must first convince the American people and Congress that the climate change problem is real and imminent.

Issues of Scale

A number of scale-related issues arise. There is a local-global continuum, i. e., continuous operations between the local and global scales, not a bipolar situation. And there are at least two ways environmental change can be thought of as global: one consists of systemic global-scale changes such as sea level rise and alterations in atmosphere chemistry; the other involves localized changes that occur in enough places to have global implications, such as loss of soil and biological diversity.

But do solutions to such global scale problems have to be global? Processes such as deforestation, drought, land degradation and migration of "environmental refugees" are shown to be, in their causes and their effects, social and environmental at one and the same time. The search for solutions leads readily to the consideration of local particularities and historical contingencies, and differential vulnerabilities. We are also led to consider the contextuality of local change. Local phenomena are influenced by institutions, processes and activities well beyond the immediate locale, and in turn, can have distant ramifications. It is through such interactions that various scales are constituted.

According to Waterstone, it is important therefore, to understand the ways in which such institutions and processes are constituted, and to illuminate the ways in which they are connected to issues of power and ultimately to vulnerability. One way to approach this matter, in the area of "global" change is through properly structured integrated assessments, and a better understanding of the opportunities to restructure individual and collective choices.

Do solutions to global scale problems have to be global? The search for solutions leads readily to the consideration of local particularities and historical contingencies, and differential vulnerabilities.

Scale in Integrated Assessments: Global Change and Local Places

Thomas J. Wilbanks

Oak Ridge National Laboratory
Oak Ridge, Tennessee

Relationships between the macro and micro scales, and the interactions between macro-structure and micro-agency, affect the way the world works and deserve more attention.

Scale is a growing issue in integrated assessments of global change. Global changes converge in localities, and changes at a local scale also contribute to global changes. Most integrated assessment to date has been top-down, i. e., scaling down from the global to the local scale, rather than bottom up. But the importance of local stake holders in determining responses to concerns about global changes is beginning to direct more attention to local and regional information and assessment. Wilbanks discussed his work on a current NASA-funded research project, Global Change in Local Places (Wilbanks, 1997), which focuses on three U. S. localities (the Blue Ridge/Piedmont of western North Carolina, the High Plains/Ogallala Aquifer area of southwestern Kansas, and the Great Lakes/manufacturing belt of northwestern Ohio), considering their greenhouse gas (GHG) emissions, driving forces, and mitigation capabilities (see Figure 1.38) at a scale of about one degree longitude by one degree latitude.

Wilbanks' thesis is that relationships between the macro and micro scales, and the interactions between macro-structure and micro-agency, affect the way the world works and deserve more attention than they have received in the global change research enterprise to date. This is not just an issue in understanding global change. Improving the understanding of linkages between macroscale and microscale phenomena and processes is one of the great overarching intellectual challenges of our age in a wide range of sciences. Biologists struggle to understand linkages between molecules, cells, and organisms; ecologists between patches, ecosystems, and biomes; and economists between firms, industries, and economies.

How Scale Matters

In theory, scale matters in studying global change, local dynamics are worth worrying about, and localities can make a difference. For instance, it is clear that some of the driving forces for global change operate at a global scale, such as the greenhouse gas composition of the atmosphere and the reach of global financial systems. But it seems just as clear that many of the individual phenomena that underlie microenvironmental processes, economic activities, resource use, and population dynamics arise at a local scale. In this paradox lies a dialectic that suggests the fundamental importance of scale. Wilbanks reviewed six basic arguments of two kinds regarding how scale matters: three arguments about the nature of reality (how the world works) and three arguments about the practice of science (how we perceive and learn about our world).

THE GLOBAL CHANGE IN LOCAL PLACES CONCEPT

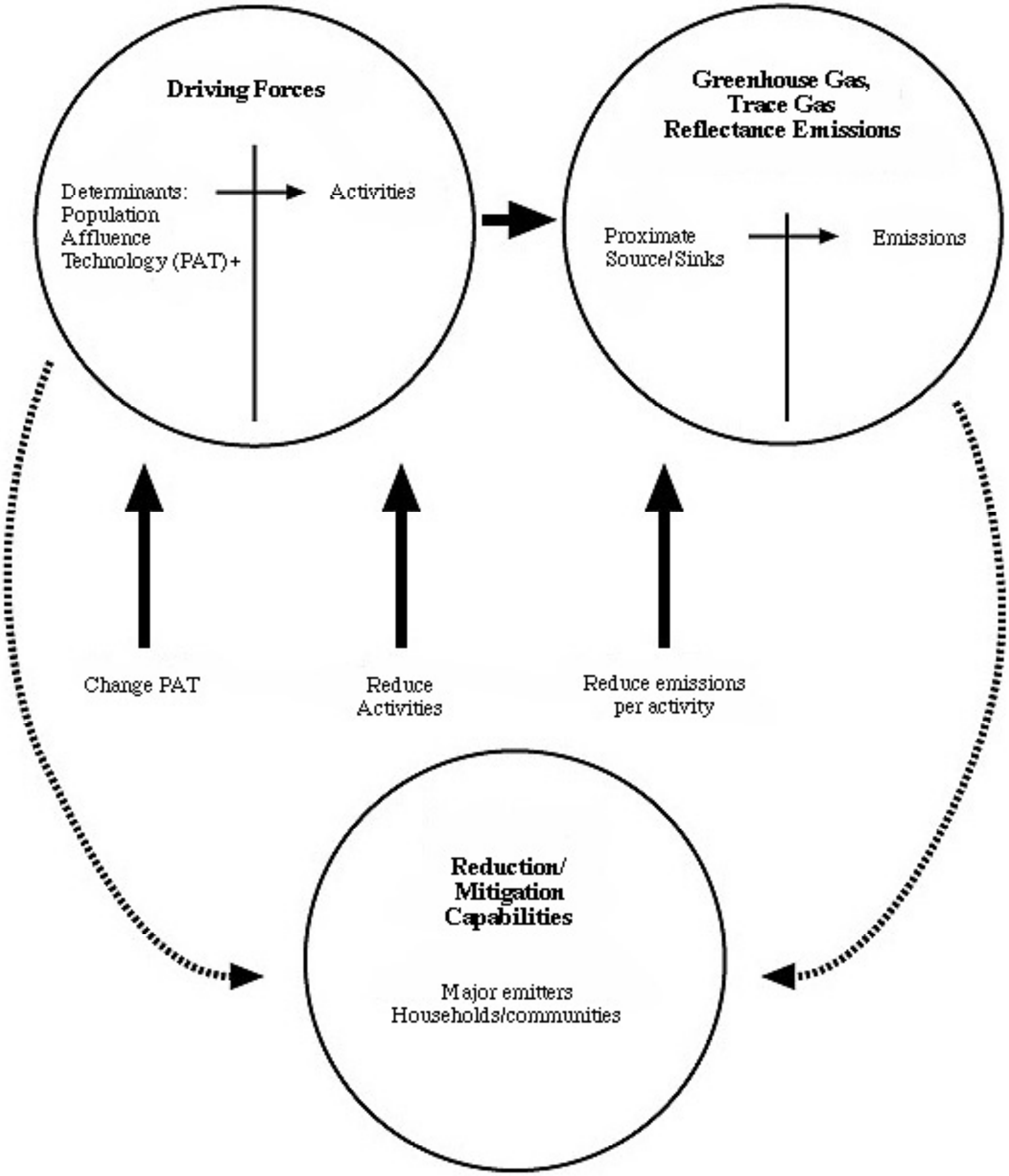

Figure 1.38

The Reality Arguments

Domain

The forces that drive global change arise from different domains of nature and society . These can be broadly divided into the systemic (e. g., the effects of greenhouse gas emissions on the global climate system) and the cumulative (when ubiquitous localized changes become global phenomenon, e. g. , local pollution or species extinction). A more detailed approach views climate, ecology, and society as the domains, each of which includes phenomena which vary in their spatial and temporal scales of operation.

Agency

Agency is intentional human action, and it takes place within a structure of institutions. The scale of sociopolitical participation is often intrinsically localized while the scale of institutional structure is almost always more encompassing. Local agency is complicated in global change issues because, e. g., the locale of emissions is not necessarily the same as the locale of control over emissions. Some local emissions can be traced to local driving forces and decisions, such as electric power generation within an area to meet its own needs, but some local driving decisions result in emissions in other areas, such as local consumption of electricity generated in other areas. And many local emissions are the result of decisions made in other areas, such as emissions from through traffic on interstate highways.

Interaction

When global structure and local agency interact across very different domains, the resulting driving forces, changes, and consequences are not readily predictable or understood. The interaction of processes moving at different time scales and areal extents underlies a great deal of the current interest in complexity, nonlinear dynamics, and the search for order amid seeming chaos. Especially in regions where human activity predominates, interactions are highly diverse and complex.

When global structure and local agency interact across very different domains, the resulting driving forces, changes, and consequences are not readily predictable or understood.

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

The Practice of Science Arguments

Tractability

It is argued that the central relationships underlying global change are too intractable, too complex to trace at any scale beyond the local, too difficult to keep grounded in direct observations, too likely to become disembodied from actual experience. The argument is that the complex relations among environmental, economic, and social processes that drive change at the global scale can only be unraveled by careful locality-specific research. The central problem in such case-specific research is that, while it is much more tractable, it is much less generalizable. Yet there are many examples of successful comparative studies using case studies which are carefully chosen for comparability and where a common protocol is used. For example, a study of poverty and environment (Kates and Haarmann, 1992) used 30

case studies from Africa, Asia, and Latin America which were not specifically designed to document poverty-environment linkages, to document the widely-held view that poverty and environmental degradation are strongly linked. The available studies told common tales of poor people's displacement from their lands, the division of their resources, and the degradation of their environments culminating in three major spirals of household impoverishment and environmental degradation driven by combinations of development/commercialization, population growth, poverty, and natural hazards. In this way, by careful comparison generic principles can emerge even from diverse case studies.

Variance

It also seems self-evident that the variance one detects in a portfolio of observations of geographic areas is likely to be greater when the areas themselves are smaller, at least if the overall geographic expanse covered by the sample is the same. For instance, the variance in greenhouse gas emissions per capita from a random sample of fifty U. S. counties would be expected to be greater than from the fifty states. In principle, this greater variety in processes and relationships at a more local scale represents an opportunity for learning more about the complex causes and consequences of global change, including the identification of interesting alternatives for mitigation and urgent needs for action that might otherwise be missed. For example, the variance in smaller-scale climates can serve as surrogates for more widespread future change. In one such study, local fluctuations were used to study the impacts of potential global warming on the runoff portion of the hydrologic cycle (Karl and Riebsame, 1989).

The greater variety in processes and relationships at a more local scale represents an opportunity for learning more about the complex causes and consequences of global change.

Perspective

Differences in perspective between macro and micro provide many examples of situations where researchers looking at an issue top-down come to different conclusions from those looking at that same issue bottom-up. A classic case is analyses of the cost of energy efficiency improvements and other approaches to limiting carbon dioxide emissions, where macroscale economic work has often estimated a significant net cost to the U. S. national economy, while microscale work in many regions of the world has consistently estimated a net benefit. Similarly, macroscale analysis of climate change impacts on agriculture finds little net loss in productivity, with one region's gains accounting for another's losses, while microlevel studies identify as especially vulnerable developing country smallholder agriculturists, pastoralists, wage laborers, urban poor, refugees, and other destitute groups. Where global change is concerned, a focus on a single scale tends to emphasize processes, information and parties influential at that scale, raising the possibility of misunderstanding cause and effect by missing the relevance of processes that operate at a different scale. Focusing exclusively at a local scale can lead to explanations in terms of local causes when some important determinants lie in processes at larger regional and global scales. Focusing exclusively on a larger scale can lead to ready generalizations that are much too general.

Scale in Integrated Global Climate Modeling

The dominant paradigm in integrated global climate modeling works from the top down, beginning with a global atmospheric circulation model which is elaborated to add more hydrological, oceanographic and vegetation features. The expanded model gives rough estimates of impacts on climate which are used to simulate possible impacts on nature and human activity. Potentials for mitigation, beginning with inventories of technologies and socioeconomic instruments are fed into an integrated model to get a sense of the costs and benefits of

alternative courses of action. There are at least 15 major integrated assessments underway worldwide. A common characteristic of these models is their low resolution; two-thirds of them have a geographic specificity of either the entire globe or of continents.

Serious mismatches in scale are apparent in the results of such efforts. Changes in atmospheric driving forces are projected at a global or major regional scale, while source and sink changes due to emissions and land use changes are essentially local (but data are scarce at a local scale). Further, there is a relatively poor fit between the scale of climate change forecasting and the scale at which weather is experienced. To date, such efforts have not provided much assistance in choosing response strategies; there has been little space-specific study of appropriate responses, reflecting a grave mismatch between availability and need. This is especially pronounced regarding adaptation potentials.

Changes in atmospheric driving forces are projected at a global or major regional scale, while source and sink changes due to emissions and land use changes are essentially local.

Relevant Current Global Change Research

In response to these problems, Wilbanks reviewed some scale-related directions in integrated global change research. The central challenges are to downscale the current top-down research paradigm to make it more useful, to incorporate the differences in perspective between top-down and bottom-up studies, and to improve understanding of what local areas and actors actually do and might want to do about global change.

In down-scaling the dominant top-down research paradigm, work is underway to improve the geographic and topical richness of global climate models, to move downscale and to cross scales more carefully, to make linkages in the integrated assessment models more relevant to local and regional concerns, and to improve the forecasts of regional (if not local) impacts and thereby encourage suitable responses. For atmospheric driving forces, the U. S.'s Country Studies program and EPA's state estimates are examples of this. For responses to climate change, the regional impacts workshops being run by the U. S. Global Change Research Program are a demonstration of this direction (see Session Two in this report). An effort to compute place-specific impacts of global climate change can be seen in a study of global agriculture by Rosenzweig, Parry and Fisher (1995). Based on projections from three global climate models, they estimate potential grain yields under several plausible scenarios for climate change, suggesting that a doubling of atmospheric carbon dioxide concentration will cause decreases in global food production.

Making the results of integrated assessments of global climate change more useful to decision makers depends fundamentally on making the results more specific to the concerns of localities and regions, the scale at which many policies are enacted and decisions made. The National Center for Integrated Assessment Research at Carnegie Mellon University, for instance, is making an effort to downscale the results of integrated assessment models. How to communicate these results is also part of the challenge, and this is the subject of research by Clark and colleagues at Harvard University.

For some perspective on local action, Wilbanks pointed to conclusions reached by a National Academy of Sciences/National Research Council committee in the 1980s. Of central importance to local action is the credibility of information, which is related to trust in intermediaries and often related to direct personal contact. The importance of local freedom and control in determining the acceptance of risk and uncertainty was also stressed. Issues affecting local action include getting on the agenda, mobilizing action, obtaining resources, maintaining policies and programs, spreading ideas and experiences among local areas, and international

linkages. Comparative case studies of lessons learned and channels of communication among local areas were also seen as important.

Tentative Conclusions About Scale in Integrated Assessments

In summary, Wilbanks offered some preliminary conclusions about scale in the integrated assessment process:

- In integrated global change research related to impacts and responses, the main current concern is with down-scaling, not up-scaling.
- It is likely, however, that far more attention will be paid in the near future to developing and using an alternative bottom-up paradigm because of the importance of a more localized scale in understanding responses to concerns about global climate change.
- Local-scale observation and measurement seems especially important for integrated assessment for understanding and documenting sources of emissions and vulnerabilities to impacts, and for shaping the political climate for national policy making.
- Local-scale observation and measurement seems less important for major driving forces: atmospheric, regulatory, industrial, demographic, and macroeconomic .
- The importance of local/regional scales for integrated assessment may depend on the degree to which environmental policies are developed and implemented in participative ways, and the degree to which true integrated understanding of processes is important for effective policy making.
- In many cases, needed local-scale data for effective integrated assessment are not routinely collected in a standardized manner. Gap-filling requirements call for data-gathering or estimation, for which standardized protocols are scarce and rarely used.
- The biggest single up-scaling problem at present is aggregating results of dissimilar local-scale case studies carried out by different people for different purposes, involving individualized approaches to data gathering and analysis.
- Upscaling may involve either the cumulating of local data into larger aggregates or effects of local phenomena on the dynamics of large systems.
- Where human actions are concerned, up-scaling increases the importance of internal versus external causes and consequences.
- Where human actions are concerned, up-scaling changes the nature of agency and control.
- There are also a number of significant up-scaling problems with spatial representation as well, e. g., with data on networks such as streams or transportation systems.
- Up-scaling and down-scaling challenges meet in determining the most appropriate scale for integrated assessment, which will vary according to the question being asked but will often be an intermediate scale.
- Considering “ideal” scales is complicated by the lumpiness of geographic and temporal data, which tend to be related to a hierarchy of data aggregation units and a periodic schedule for data collection.
- The biggest single up-scaling problem at present is aggregating results of dissimilar local-scale case studies carried out by different people for different purposes.

Making the results of integrated assessments of global climate change more useful to decision makers depends fundamentally on making the results more specific to the concerns of localities and regions.

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Up-scaling and down-scaling challenges meet in determining the most appropriate scale for integrated assessment, which will vary according to the question being asked but will often be an intermediate scale.

Scale Dependence and Atmospheric Chemistry

Donald J. Wuebbles

University of Illinois
Urbana, Illinois

A number of issues in atmospheric chemistry relate to scale. In global change research, there is concern about changing atmospheric composition due to emissions of carbon dioxide, nitrogen oxides, chlorofluorocarbons and their replacements, methane, and other gases potentially important to climate. The relationship between the biogeochemical cycles at the land-biosphere-ocean interface with the atmosphere are of critical interest with regard to atmospheric composition. Local emissions, particularly from large urban areas, can lead to regional changes, such as acid rain, as well as to global changes. There is still much that is not understood about this interface between the local level and the regional and global levels.

There is a need to downscale and see how changes occurring globally will lead all the way down to changes in the biosphere.

A hierarchy of methods and models are used in biogeochemical cycle research, and there is a range of transitions in going from one type of model to another. Table 1.39 summarizes the scales of different types of models. There is a need to downscale and see how changes occurring globally will lead all the way down to changes in the biosphere. An example of this kind of effect is that the period from 1991 to 1993 saw sharp reductions in the rates of increase of carbon dioxide, carbon monoxide, nitrous oxide, and methane, probably as a result of the 1991 Mt. Pinatubo eruption, the aerosols from which led to a cooling effect and a decrease in the amount of solar radiation reaching Earth's surface, and to feedbacks in the biosphere.

	Urban-Scale	Regional-scale	Global-scale
Time duration	< 48 hours	< 7 days	months to years
Space domain	50 x 50 km^2	2000 x 2000 km^2	global
Vertical extent	1 - 2 km	10 - 15 km	10 - 80 km
# of chemical species	> 40	> 60	> 50
Microphysics	-	cloud and aerosol	simple
Removal	simple	detailed (wet and dry)	simple
Grid Size	1 - 5 km	10 - 100 km	> 250 km

Table 1.39

Size and Scale of Different Types of Models

Spatial and Temporal Scales in Atmospheric Chemistry

Atmospheric chemists study processes affecting atmospheric chemistry at spatial scales ranging from urban (~10 km) to global (~106 km) and time scales extending from hours to years. The spatial and temporal scale of interest is set primarily by the lifetime of the trace

gas affecting the problem and the relevant transport scales. Among the important transport timescales: north-south mixing in the troposphere is of the order of one year; mixing from the boundary layer to the upper troposphere (the so-called turn over time for the troposphere) is of the order of one month; and the time scale for exchange between the stratosphere and troposphere is estimated to be around three years.

These transport timescales are then related to the atmospheric lifetimes of gases. For example, many halocarbons have lifetimes extending into tens of years, so the only relevant transport scale of interest would be the stratosphere-troposphere exchange. For trace gases with lifetimes less than five years, the removal process in the troposphere by oxidation and physical mechanisms becomes relevant. For trace gases with lifetimes close to a year (the interhemispheric exchange time) the location of the sources is important as there is not enough time to mix the trace gases uniformly in the troposphere (e. g., emissions from the northern hemisphere that do not reach the southern hemisphere). With trace gases that have lifetimes of months, the vertical mixing gains importance as the lifetimes approach the scales of the vertical mixing. Thus, the problem steadily cascades down to smaller and smaller scales as the lifetime of the trace gas under consideration decreases.

Wuebbles discussed the emissions of interest with regard to global change (summarized in Table 1.40). Gases with long atmospheric lifetimes and important effects on climate are of particular concern, such as the fluorocarbons which are being proposed as substitutes for CFCs but have lifetimes of thousands of years and are strong greenhouse gases (GHGs).

Some Relevant Chemical Symbols and Abbreviations

CO2	carbon dioxide
OH	hydroxyl
N2O	nitrous oxide
NO	nitric oxide
NO2	nitrogen dioxide
NOX	nitrogen oxides (NO + NO2)
CH4	methane
CO	carbon monoxide
O3	ozone
SO2	sulfur dioxide
NMHC	non-methane hydrocarbons
CFC	chlorofluorocarbon
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
PFC	perfluorocarbon
PAN	peroxyacetyl nitrate
GHG	greenhouse gas

Gas	**Lifetime**	**Dispensation**
CO_2	variable (years)	flux to oceans and biomass
N_2O	120 years	destroyed in stratosphere
CFCs	> 50 years	”
Halons (H - 1301)	> 20 years	”
HCFCs	months - years	destroyed by tropospheric OH
HFCs	years	”
CH_4	8 - 10 years	”
NMHCs	hours- years	”
PFCs	1000s years	destroyed above mesosphere
NO_x	hours- days	OH, O3
CO	month	”
SO_2	weeks	OH

Table 1.40
Major Emissions of Interest for Global Change Research

The hydroxyl radical (OH) is the primary oxidizing species in the atmosphere, making it a very prominent gas in terms of atmospheric control of many gases of interest. Carbon monoxide (CO), for example, is largely controlled by OH. Methane and CO have both natural and anthropogenic sources. OH concentration is affected by ozone, water vapor and nitrogen oxides. OH, CO and CH4 form a triangle of interactions that control their decay rates. In addition, the lifetimes of HCFCs and HFCs are sensitive enough to the abundance of OH that if human activity were to dramatically decreases the OH level in the atmosphere, it could allow HCFCs and HFCs to reach the stratosphere where they could destroy ozone (sufficient OH would otherwise destroy these in the troposphere). With a lifetime of seconds (determined locally), and many important interactions, including potential climatic feedbacks, OH has significant effects globally, but we do not have a thorough understanding of it yet.

Scale Dependence of Ozone Production in the Troposphere

One way that scale dependence in the troposphere occurs is due to nonlinear production location efficiency of ozone (O3) from NO and NO2 (NOX). NOX destroys O3 in the stratosphere but produces it in the troposphere due to the different type and amount of solar radiation present. Ozone production efficiency depends on the concentration of NOX and non-methane hydrocarbons (NMHC) and the ratio of NMHC to NOX. When NOX concentrations are greater than 1 part per billion (ppb), there is less efficient production of O3 per molecule of NOX . When NOX concentrations are less than 1 ppb there is more efficient production of O3 per molecule of NOX. Therefore, diluting NOX emissions over a large domain in a model results in excess production of O3. For this reason, current atmospheric chemistry models tend to produce too much ozone in the troposphere.

Gases with long atmospheric lifetimes and important effects on climate are of particular concern, such as the fluorocarbons.

Regarding scale and dimensionality, Wuebbles says that two-dimensional atmospheric chemistry models are adequate for understanding many processes in the stratosphere but that three-dimensional models are needed for most tropospheric research. A recent study by Crutzen, et al. comparing 2-D and 3-D models shows that 2-D models don't represent tropospheric processes very well. The ratio of results from the 2-D to the 3-D model reveals that one can get a 100 percent difference in OH concentration near the equator in the troposphere. The 2-D model has too much mixing and shows different responses for a variety of species than the 3-D; the largest differences are in lower troposphere though significant differences are found in the upper troposphere as well. However, this conclusion may be affected by the particular models used and may not be a general rule.

Effects of Small Scale Processes on Global Chemistry

Small scale processes effect global chemistry through the transport of reservoir species from source regions to remote regions and the subsequent effect on chemistry. For example, peroxyacetyl nitrate (PAN), a complex hydrocarbon with a lifetime of the order of weeks to months, is transported from the polluted regions in which it is formed to relatively cleaner regions of the troposphere. This leads to a redistribution of ozone precursors from small scale polluted urban areas to the remote troposphere.

In addition, rapid transport of ozone precursors from the boundary layer to the upper troposphere occurs through deep cumulus convection, thereby affecting global scale chemistry. Deep convection occurs on small spatial and time scales and is essentially a sub-grid scale process in terms of global scale models. NOX has a lifetime of a few hours in the boundary

layer and a lifetime of over a week in the upper troposphere. Thus, the small scale convection process extends the lifetime of this ozone precursor and can lead to a spatially extended impact on background atmospheric ozone levels due to anthropogenic emissions.

How can such processes be treated in a model when such a small fraction of the grid space is involved? There is ongoing work to improve model parameterizations of such sub-grid scale processes so that they more closely match the data (which are of increasing quality). A recent observational study shows that cumulus convection can actually bring stratospheric ozone down into the troposphere; this could have negative effects on agricultural production, for instance.

Solving Scaling Problems

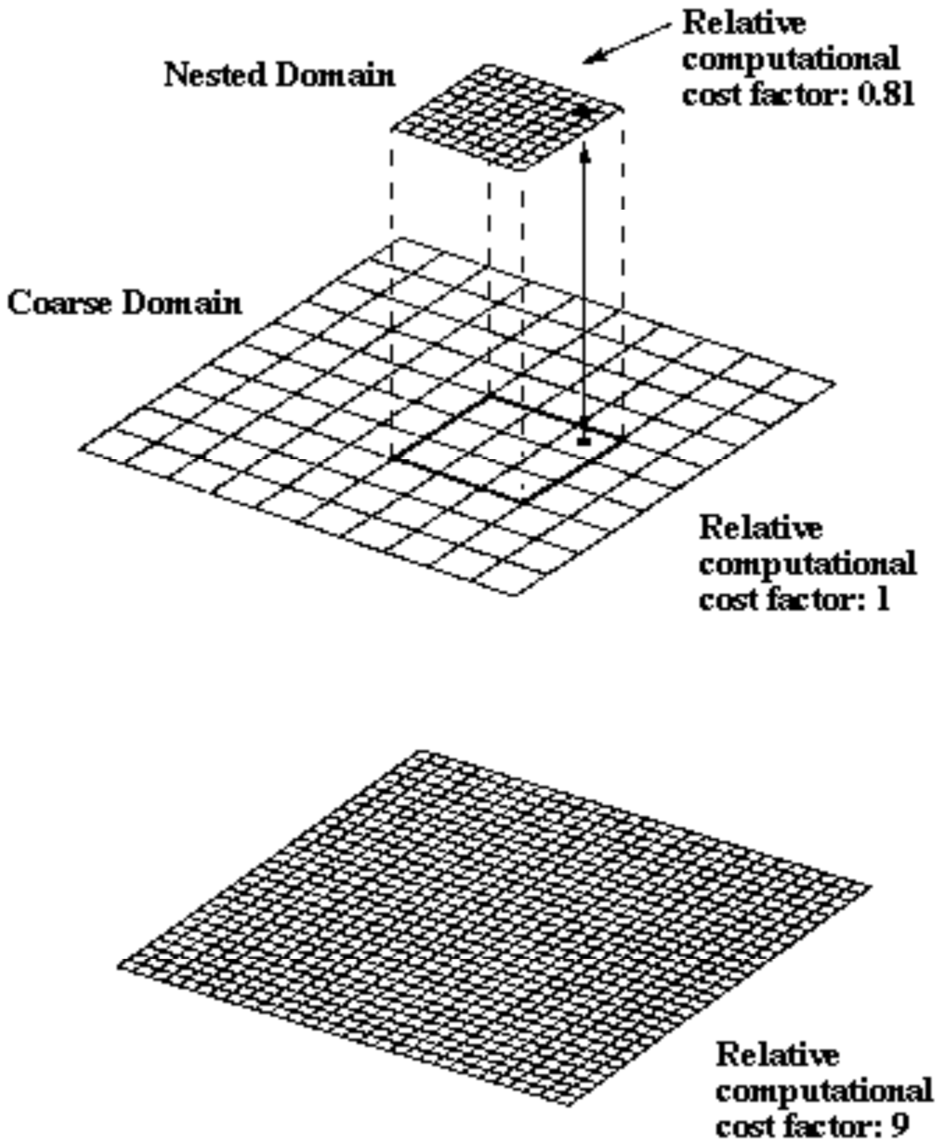
Two-dimensional atmospheric chemistry models are adequate for understanding many processes in the stratosphere but three-dimensional models are needed for most tropospheric research.

Wuebbles discussed a number of methods of solving scaling problems in atmospheric chemistry. One option is to reduce the model grid size or use special grids. Another is the use of nested grids or telescoping grids. This method, which involves increasing the resolution of a limited subdomain while leaving the larger domain at a coarser resolution is illustrated in Figure 1.41. A third is the coupling of local/regional /urban models with global scale models. Such coupling is a challenge because the global models can not include as detailed chemistry as the smaller scale models.

As an example, Wuebbles showed results from the Air Quality Model (AQM) of Julius Chang and others developed at State University of New York at Albany. The modeled area is central California, including the San Francisco area, at a 12 x 12 km grid resolution. This resolution could not capture the detail necessary, so, within this, three regions of particular interest (Bakersfield, Fresno and the Bay area) were treated with 4 x 4 km two-way nested grids in which special calculations were applied. This captures the needed detail in most important areas without the tremendous computational expense (9 times greater) of going to a 12 x 12 km grid for the entire domain. The differences between the 12 x 12 results and the results using the nested 4 x 4 grids become greater the longer the model is run; by the fifth day the differences are large.

In another example, adding a Surface Layer Submodel (sls) to the AQM model added important information to its results. Urban/regional models generally have a 50-100 meter surface layer (nearest the ground). However, in many regions, especially at night, the bottom boundary layer is actually very close to the ground - just tens of meters. By dividing the surface layer into four sub-layers with the bottom zone being just 10 meters, a greater simulation of reality is achieved. In the less-resolved model, large amounts of NOX appear all the way to the ground. But when the sls is added, the NOX appears in the second layer from the ground, which represents with more accuracy what actually happens at night in urban areas. During the day, there is not much difference between the two models, but at night, it is quite significant. With the sls included, the NOX available for producing ground level ozone compares well with observations. It is important to understand the mechanisms of the chemistry involved and attempt to reproduce them in the models.

With regard to global change issues, scaling up from the local to the global scale involves atmospheric chemistry with significant effects on the troposphere (far less in stratosphere). Scaling down from the global to the local and urban scales involves many important climate-related changes including changes in water vapor, local temperature , clouds, etc., and these can then cause feedbacks up to the global scale.



A recent observational study shows that cumulus convection can actually bring stratospheric ozone down into the troposphere; this could have negative effects on agricultural production.

Several Methods for Increasing Model Resolution over Limited Subdomains

Figure 1.41
Diagram of the nested grid concept and its computational cost savings

Participant Roster

Scaling from Site-Specific Observations to Global Model Grids

Chair, Dr. Danny Harvey, University of Toronto

July 7-17, 1997

Dr. Roni Avissar
Department of Environmental Sciences
Rutgers University

Dr. Larry Bird
Department of Global Change
University of Toronto

Dr. Herald Bugmann
Department of Global Change & Natural Systems
Potsdam Institute for Climate Impact Research

Dr. William Gough
Environmental Science
University of Toronto at Scarborough

Dr. Chris Green
Department of Economics
Mc Gill University

Dr. Myron P. Gutnam
Department of History
The University of Texas at Austin

Dr. John Harte
Energy and Resources Program
University of California, Berkeley

Dr. Danny Harvey
Department of Geography
University of Toronto

Dr. Martin I. Hoffert
Physics Department
New York University

Dr. Lyn McNutt
Geophysical Institute
University of Alaska

Dr. Karen O'Brien
Center for International Climate and Environmental Research - Oslo (CICERO)

Dr. Garry Peterson
Department of Zoology
University of Florida

Dr. Roger Pielke, Sr.
Department of Atmospheric Science
Colorado State University

Dr. Dale S. Rothman
Sustainable Development Research Institute
University of British Columbia

Dr. Elena Shevliakova
Center for Human Dimension of Global Change
Carnegie Mellon University

Dr. Richard C. J. Somerville
Climate Research Division
Scripps Institution of Oceanography
University of California, San Diego

Aspen Global Change Institute
100 East Francis Street
Aspen CO 81611
http://www.agci.org
970 925 7376
agcimail@agci.org

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