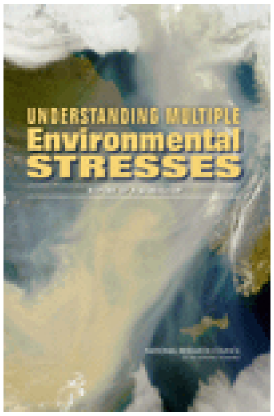

**Understanding Multiple Environmental Stresses: Report of a Workshop**

Committee on Earth-Atmosphere Interactions: Understanding and Responding to Multiple Environmental Stresses, National Research Council

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# UNDERSTANDING MULTIPLE Environmental STRESSES

## REPORT OF A WORKSHOP

Committee on Earth-Atmosphere Interactions:
Understanding and Responding to Multiple Environmental Stresses

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
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# Preface

Periodically the Board on Atmospheric Sciences and Climate (BASC) works with its federal agency partners to select a topic for a special workshop, sometimes called our "summer study." The purpose of the workshop is to provide an opportunity for scientists, industry, and agency staff to explore current issues in an interactive format. Sometimes these workshops address practical problems, such as communicating uncertainties in weather forecasts (NRC, 2003), and other times specialized technical issues, such as improving the physical parameterizations in coupled atmosphere-ocean-land models (NRC, 2005a). Often, such as in this report, an issue is selected that might otherwise go unstudied due to the scale, scope, or tractability of the problem.

The 2005 BASC workshop focused on multiple environmental stresses in the earth-atmosphere system (see Appendix A for Statement of Task). Historically, environmental problems have been studied one at a time and sector by sector (e.g., the impacts of air pollution on human health or the impacts of invasive species on fisheries). Although this approach has enabled researchers to make good progress in many areas in characterizing cause-effect environmental relationships that are linear in nature and limited in scale, it does not consider the composite effects of simultaneous environmental changes. Unless we consider robust options that solve multiple problems and prevent new ones, we may be ineffective and inefficient in our environmental efforts. Some of these issues are addressed in other National Research Council reports (e.g., NRC, 1999, 2002).

This workshop[1] was intended as a step in identifying the types of near-term and long-term research needed to understand multiple environmental stresses and explore integrated strategies to address them. It was planned and facilitated by a five-person steering committee and was held September 29-30, 2005, at the Arnold and Mabel Beckman Center of the National Academies in Irvine, California. More than 25 experts from a variety of disciplines and perspectives, including both the natural and social sciences, attended, as well as managers and stakeholders in various sectors and regions (see Appendix B for the workshop agenda and Appendix C for the participant list). The participants were charged to explore current understanding of multiple environmental stresses in the earth-atmosphere system and to discuss the types of research needed to improve integrated understanding and response strategies for these kinds of complex, nonlinear problems. To focus the discussions, two case studies were selected and participants were assigned to come prepared with short talks on aspects of these cases; other participants were assigned to lead discussion sessions to explore the issues and generate ideas about research needs. This report is the steering committee's summary of these presentations and the associated discussions; abstracts of the participants' talks are included as Appendix D. The workshop was funded using support provided from the National Science Foundation, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and Environmental Protection Agency.

On behalf of the Board on Atmospheric Sciences and Climate and the National Academies, I would like to express great thanks to the steering committee for its leadership and to all the workshop speakers and participants for their time and thoughtful comments. Although a workshop by definition can only explore issues and not provide truly detailed or deliberative recommendations, this workshop report should prove useful to researchers and agency program managers looking for opportunities to address these complex issues.

Chris Elfring, Director
Board on Atmospheric Sciences and Climate

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[1] Following standard National Academies procedures for workshops, this report captures the discussions and presentations that occurred during the two-day event; it does not contain recommendations.

# Acknowledgments

This workshop report was written by the workshop steering committee based on the presentations and discussions at the workshop, and we appreciate the input from all the participants. In addition, this report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

M. Joan Alexander, NorthWest Research Associates/CORA, Boulder, Colorado
Eric J. Barron, University of Texas at Austin
Julio Betancourt, University of Arizona, Tucson
Scott C. Doney, Woods Hole Oceanographic Institution, Massachusetts
Kelly T. Redmond, Desert Research Institute, Reno, Nevada
William H. Schlesinger, Duke University, Durham, North Carolina

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Elbert W. Friday, Jr., University of

Oklahoma. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

# Summary

The research of the last decade has demonstrated that ecosystems and human systems are influenced by multiple factors, including climate, land use, and the by-products of resource use. Understanding the net impact of a suite of simultaneously occurring environmental modifications is essential for developing effective response strategies. This suite of simultaneous influences, or multiple environmental stresses, produces more than simply additive impacts. The term means that there is a confluence and interaction of stresses that both accumulate and, because of feedbacks, increase or become more complex. Multiple environmental stresses in composite lead to qualitatively and quantitatively different outcomes from single influences, and thus research that seeks to better understand these multiple stresses requires thinking differently from that used in traditional, sectoral, or single-problem approaches.

There are no generally agreed upon methodologies for studying complex systems of interconnected environmental influences that can have different impacts in varied and sometimes subtle directions. Understanding multiple stresses almost always requires consideration of multiple variables, nonlinear processes, and a variety of spatial and temporal scales. We typically have only a rudimentary understanding of the dynamics of interactions between different environmental variables in complex systems, making it extremely difficult to predict the combined effects of multiple interacting stresses. In addition to gaps in the scientific understanding of multiple environmental stresses, there is a lack of understanding of how to move from understanding to management and policy decisions, and in particular how to devise options that make sense in the face of significant uncertainties.

The concept of multiple environmental stresses taken alone can seem vague, and thus the steering committee organized this workshop around two examples to provide different perspectives on multiple stress scenarios. The first case selected was drought, a complex environmental condition that both is driven by multiple environmental stresses and leads to multiple stresses across a wide range of time and spatial scales. Drought is a normal climate variation that can vary in magnitude and intensity, and it provides a clear illustration of the feedbacks involved both in the occurrence of the natural event and in the human activities that may alter societal vulnerability (e.g., population growth, water management policies, and changes in land cover). The second case selected focused on a wide range of atmosphere-ecosystem interactions that taken together reflect characteristics of multiple, simultaneous environmental stresses.

These two cases were selected because they offer very different problems, scales, and lessons. Because of this, the presentations and discussions—and the respective chapters in this report—are not perfectly parallel. Despite the differences in approach, the workshop participants did identify some important commonalities. As discussed in Chapter 4, the overarching lesson of the workshop is that society will require new and improved strategies for coping with multiple stresses and their impacts on natural and socioeconomic systems. Improved communication among stakeholders, increased observations (especially at regional scales), improved model and information systems, and increased infrastructure to provide better environmental monitoring, vulnerability assessment, and response analysis are all important parts of moving toward better understanding of and response to multiple-stresses situations.

Workshop participants identified the development of comprehensive regional frameworks for conducting environmental studies as a key part of understanding multiple environmental stresses:

1. An integrated regional web of sensors that links existing observations into a coherent framework
2. An integrated and comprehensive regional information system accessible to a wide variety of researchers, operational systems, and stakeholders
3. Directed process studies designed to examine specific phenomena through field study
4. Complex coupled system models at the spatial and temporal scales appropriate to study specific and integrated biologic, hydrologic, and socioeconomic systems
5. A strong connection to significant regional issues and stakeholders.

Workshop participants identified the Regional Integrated Sciences and Assessments program (RISA) as a possible model for such regional frameworks. Overall, the degree to which progress is made on complicated environmental problems is proportional to the degree we are able to implement these five organizing principles, and progress will be limited if we cannot. This will take a major reorganization in how we approach multifactor environmental problems and thus will be difficult.

As an outcome of the workshop, seven near-term opportunities for research and infrastructure that could help advance our understanding of multiple stresses and make this understanding useful to decision makers were proposed. These are discussed in more detail in Chapter 4.

1. Building a new U.S. ground-based ecological measurement network to understand multiple stresses at multiple scales
2. Enhancing global information systems and satellite observations
3. Synthesizing existing data to identify status and trends in ecosystems
4. Analyzing extreme events of record to identify nonlinearities and thresholds for future change
5. Identifying technologies, management, or institutional mechanisms to enhance resilience
6. Developing regional foci to understand vulnerability and coping capacity in particular places
7. Increasing stakeholder involvement to help identify problems and solutions and provide ideas on the kinds of information needed (and in what format) to be useful for decision making.

# 1

# Introduction[1]

## DEFINING THE CONCEPT OF "MULTIPLE STRESSES"

Natural, managed, and socioeconomic systems often experience multiple environmental stresses that can come together to cause impacts that are greater than simply additive. Multiple environmental changes can also interact with each other to cause additional unexpected stresses. The term "multiple stresses" is simply a shorthand way of referring to scenarios where multiple environmental influences are at work with various multidimensional interactions among them. Understanding the net impact of a suite of simultaneously occurring environmental modifications (e.g., elevated carbon dioxide; increased oxidants, reactive nitrogen, and acid deposition; decreased stratospheric ozone; increased ultraviolet radiation; higher mean temperature; changes in timing and availability of water; loss of biodiversity, increases in invasive species, rising sea level; coastal development and habitat fragmentation) is essential for developing predictive capabilities and response strategies.

There are no generally agreed upon methodologies for studying complex systems of interconnected environmental influences that can have different impacts in varied and sometimes subtle directions. Understanding multiple stresses almost always requires consideration of multiple variables, nonlinear processes, and a variety of spatial and temporal scales. However, we typically have only a

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[1] Much of the material in this introductory chapter is taken from the workshop's keynote address by Dr. Eric Barron, University of Texas at Austin, who was asked to define terms and provide context for the workshop.

rudimentary understanding of the dynamics of interactions between different environmental variables in complex systems, making it extremely difficult to predict the combined effects of multiple interacting stresses. Other scientific challenges include understanding the multiple time and space scales on which these interactions take place, developing indicators for "threshold" responses that may lead to sudden and dramatic changes in societal or environmental structure and function, characterizing and quantifying risks and vulnerabilities, and understanding the economic impact of multiple interacting changes. Another critical challenge is proceeding with decision making given the many uncertainties and limited prediction capabilities.

Given the highly interdisciplinary nature of multiple environmental stresses, conducting research on the topic involves a variety of infrastructural and institutional challenges. First, a broad range of observational and experimental/process studies is needed for understanding integrated climate and ecosystem processes. Second, coupled biophysical and biogeochemical models are needed to address the dynamics of exchange of water, energy, carbon, and nitrogen on multiple timescales, with biogeographic models that simulate the effects of climate and other factors on vegetation distribution. New data and information systems may be necessary to enable scientists to integrate knowledge across these disciplines. Further, it appears likely that focusing on natural, managed, and socioeconomic systems on a regional scale may provide a tractable approach to bringing together the diverse researchers and knowledge needed to improve understanding of multiple environmental stresses.

In addition to gaps in the scientific understanding of multiple environmental stresses, there is a lack of understanding of how to devise wise management and policy approaches that address suites of problems and, in particular, options that make sense in the face of uncertainty. These options can be technological, managerial, or institutional and will require much more integrative research in many disciplines. It will also require serious consideration of how we translate information as well as a sense of what we do not know or cannot know, so that it is useful to those who must make decisions. Adaptive management using the best information available, while retaining flexibility to make changes, requires managers to think differently, but it does increase resiliency to risk.

Effective communication between researchers and stakeholders is critical. As research develops more sophisticated understanding of environmental systems and how multiple stresses interact and compound, it becomes even more difficult to translate this understanding to those who must use the information. Although there is no easy answer to this dilemma, the solution appears to require extended interactions, careful attention to including all perspectives, and frankness about the level of certainty and uncertainty of the information.

## THE NATURE OF THE PROBLEM

The nature of the environmental issues facing any nation demands a capability that allows us to enhance economic vitality, maintain environmental quality, limit threats to life and property, and strengthen fundamental understanding of Earth. In each case it is the ability to anticipate the future (e.g., forecasting an impending storm, predicting water quality change in response to a new source of pollutant) that makes information about the earth system truly useful. Reliable information about the future (i.e., forecasts or predictions) is essential when addressing environmental issues. Thus, society requires greater access to and greater confidence in both information and forecasts or projections in order to weigh the advantages and risks of alternative courses of action. Such information is a key commodity in enhancing economic vitality and societal well-being. What stands in our way of providing this information?

Many of the driving forces that alter environmental quality are widely recognized and involve primarily weather and climate, patterns of land use and land cover, and resource use with its associated waste products. A key feature of most regions is that more than one driving force is changing simultaneously. Consequently, most locations are characterized by multiple stresses. The effect of a combination of environmental stresses is seldom simply additive. Rather, they often produce amplified or damped responses, unexpected responses, or threshold responses in environmental systems. Multiple, cumulative, and interactive stresses are clearly the most difficult to understand and hence the most difficult to manage.

In contrast to how the real world works, most research and policy focuses on discrete parts of these complex problems. Basically, earth and environmental sciences tend to focus on cause and effect, where we seek to understand how a specific element of the system may respond to a specific change or perturbation (e.g., the impact of acid rain on lake fisheries). The lack of methods to assess the response of the system to multiple stresses limits our ability to assess the impacts of specific human perturbations, to assess advantages and risks, and to enhance economic and societal well-being in the context of global, national, and regional stewardship.

The problem is not limited simply to moving from analysis of discrete parts of complex problems to a more comprehensive analysis. First, economic vitality and societal well-being are increasingly dependent on combining global, regional, and local perspectives. A "place-based" imperative (i.e., site specific) for environmental research stems from the importance of human activities on local and regional scales, the importance of multiple stresses on specific environments, and the nature of the spatial and temporal linkages between physical, biological, chemical, and human systems. We find the strongest intersection between human activity, environmental stresses, earth system interactions, and human decision making in regional analysis coupled to larger spatial scales.

Second, although a decade of research on greenhouse gas emissions, ozone depletion, and deforestation has answered some critical questions, the last decade of effort has also revealed a number of new challenges. The most notable is the challenge of creating integrated global observation capabilities and the computational and scientific limitations inherent in creating a truly integrated, global, coupled system modeling capability suitable for assessing impacts and adaptations. These problems are noteworthy in global change science, but they become intractable at the scales of human decision making. A major part of the problem is simply a matter of scale and the sheer volume of information required to combine physical, biological, chemical, and human systems if the framework is global. For example, whereas a global integrated observing system is challenging but tractable and plays a fundamental role on the scale of a global circulation model, it collapses under its own weight at higher spatial resolutions if we demand a truly comprehensive data system involving the host of observations spanning biology, hydrology, soils, weather, etc., required to address problems at the scales of human decision making.

Recognition of the importance of developing a more integrated approach to environmental research was made abundantly clear in the National Assessment Synthesis Team's report, *Climate Change Impacts on the United States* (NAST, 2000). The first recommendation for future research focused on developing a more integrated approach to examining impacts and vulnerabilities to multiple stresses. The report contains many examples where the key limitation to the assessment of potential impacts on climate was a lack of knowledge of other stressors. For example, changes in insect-, tick-, and rodent-borne diseases could be clearly tied to weather and climate, but the number of other environmental factors that could influence the disease vectors (e.g., the importance of land use on disease hosts), transmission dynamics, and population vulnerabilities severely limited our ability to make robust conclusions on how climate change might influence the distribution and occurrence of many infectious diseases in the future.

Why, with so many pressing problems demanding research attention, should the United States give more focus to multiple stresses in environmental research? The driving forces that alter environmental quality and integrity are often well known, but most regions experience multiple simultaneous environmental changes, and the combined effects of these changes are much more difficult to understand and manage than the discrete issues that most research, analysis, and policy focus on. This lack of appreciation for, and understanding of, multiple stresses limits our ability to assess the impacts of specific human perturbations, to assess advantages and risks, and to enhance economic and societal well-being in the context of global, national, and regional stewardship. However, the solution to this problem is not simply increasing the scope of our analysis, but rather developing a more focused and integrated approach to environmental research.

## WHAT ASSESSMENTS CONCLUDE ABOUT RESEARCH NEEDS

Many national and international assessments of environmental issues have been conducted in the last two decades, such as the ozone assessments (WMO/UNEP, 1985, 1989, 1991, 1994, 1998, 2002), the Intergovernmental Panel on Climate Change assessments (IPCC, 1990, 1995, 2001), the U.S. National Assessment (NAST, 2000), and the Millennium Ecosystem Assessment (MEA, 2005). Each of these multiyear efforts involving thousands of scientists, government officials, and stakeholders has made significant contributions by summarizing the state of science and characterizing remaining uncertainties. What is lacking, however, is a strategic research plan that could emanate from these assessments.

After assembling the data that are available, assessment researchers are keenly aware of what was not there and which gaps are most critical to fill to enhance understanding. Taking time at the end of assessments to characterize what is known, what is not known, what is knowable in what time frame, and what is most important to know to assist timely decision making would generate much-needed short-term and long-term research strategies. These strategies would be valuable to governments and researchers in thinking about appropriate budgets across agencies, across disciplines, across space, and over time to answer societal questions.

Especially in times of tight budgets, all desired research cannot be conducted simultaneously. Missing information about scientific processes, technological promise, institutional mechanisms, ecological or socioeconomic thresholds, and behavioral change all need to be developed, but some missing pieces of the puzzle may be more crucial to pursue in order to find robust solutions. And some questions are more tractable than others.

## INTRODUCTION TO THE CASE STUDIES

The concept of multiple stresses, taken alone, can seem vague, and thus the steering committee decided to focus on two concrete examples that were selected to provide different perspectives on multiple-stresses scenarios. The first case study selected for examination was drought, a complex environmental condition that both is driven by multiple environmental stresses and leads to multiple stresses across a wide range of time and spatial scales. Drought is a normal climate variation that can vary in magnitude and intensity, and while it is not the only climate-induced generator of multiple stresses, it is a significant one and one that provides clear illustration of the feedbacks involved. The second case study selected for attention focused on a wide range of atmosphere-ecosystem-human interactions that, taken together, reflect characteristics of multiple simultaneous environmental stresses. For each case, workshop participants discussed the current state of understanding, what can be learned from prior unexpected findings, vulnerability and future socioeconomic impacts, and potential response strategies.

Participants then stepped back from the examples in search of common lessons that might be learned.

Drought, in general, originates from a deficiency of precipitation over an extended period, resulting in a water shortage for some activity, group, or environmental sector. Workshop participants discussed the current state of the knowledge base concerning the causes, frequency, intensity, and predictability of drought at multiple spatial scales within the continental United States and how societal changes (e.g., increasing population) affect vulnerability to drought at local and regional scales. The question of how the United States could facilitate development of a risk-based drought management approach directed at increasing resilience and decreasing vulnerability was highlighted.

The second case study looked at atmosphere-ecosystem interactions. In the earth system, both the dynamics and composition of the atmosphere affect the biosphere. In turn, uptake, storage, and emissions by the biosphere affect the composition and dynamics of the atmosphere. Changing atmospheric conditions (e.g., changes in chemical composition and physical characteristics) together constitute multiple stresses to ecosystems, and the resultant ecosystem impacts and atmospheric feedbacks are poorly understood. Workshop participants addressed how global/climate change drivers affect atmospheric composition and dynamics and subsequent atmosphere-ecosystem interactions, as well as the socioeconomic impacts of climate change on agriculture and carbon cycling, capture, and sequestration as regards agriculture and forestry.

For both case studies the steering committee asked participants to explore the historical record and identify unexpected findings that raise concern about future responses to multiple stresses. In addition, the steering committee asked participants to focus on areas where large uncertainties lie, processes that are nonlinear and where predicting the integrated effect of multiple stresses is especially difficult, and on observed and potential thresholds (changes of state) that may be beyond our current ability to predict. The steering committee also recognized important commonalities between the two cases and sought to draw broader lessons about multiple stresses or multiple drivers. The workshop also explored lessons learned from the Millennium Ecosystem Assessment (MEA, 2005) because this document provides a comprehensive summary of the state of the world's ecosystems and services and how they may change in the future. Finally, workshop participants were asked to engage in a synthesis discussion addressing tools, nonlinearities and thresholds, resilience, and the use of regional studies.

## NONLINEARITIES, THRESHOLDS, AND THE VULNERABILITY-RESILIENCE CONTINUUM

In considering multiple stresses with respect to atmosphere-ecosystem interactions and drought, we need to make explicit our conceptions of four critical concepts: nonlinear responses, thresholds, vulnerability, and resilience. The workshop organizers defined nonlinearity according to the approach adopted by Rial et al. (2004), in which systems so characterized display significant imbalances between inputs and outputs, primarily (although not exclusively) episodic and abrupt rather than slow and gradual change, and multiple equilibria. In such systems small changes in parameters often cause large changes in the behavior of the system. Nonlinearity also often confronts, if not causes, thresholds (i.e., phase changes) in a system that are not easily reversible. The global climate system is inherently nonlinear and quite complex and consequently generates a wide variety of thresholds for natural ecosystems and human social systems. But humans themselves now generate planetary-scale environmental effects, including modification of the global climate system. The interaction of these two drivers multiplies the stresses that ecosystems and human social systems must face. Because the climate system is highly nonlinear and coordination and control of human forcing is weak, thresholds are encountered quite often. These thresholds present severe policy challenges. Thresholds also raise questions about vulnerability and resilience of both ecosystems and human social systems. Vulnerability refers to magnitudes and rates of environmental change that exceed the capacity of ecosystems and human social systems to cope and recover. These systems then either break down or exhibit a variety of pathologies under those conditions. Resilience, on the other hand, refers to a capacity to adapt to and cope with the level of stress imposed, even if damage to the system results.

The application of these concepts can be illustrated with respect to the issue of drought. In Figure 1-1, Wilhite and Buchanan-Smith (2005) illustrate the important differences between societies that are either vulnerable to or resilient in the face of drought. (Box 1-1 defines vulnerability, resilience, and other relevant terms.) The figure shows that societal vulnerability begins with exposure to drought in the absence of either risk-based drought management policies or an early warning system. Vulnerability is then enhanced by multiple-stresses problems in the form of marginalized groups who lack resources, options, and ways of mitigating drought impacts. Vulnerability is also enhanced by previously existing problems of dependence on the overexploitation of natural resources, poverty, and violent conflict. As the drought event intensifies, society resorts to crisis management in the face of potential disaster. How then is resilience to be developed? The two most critical steps represent the development of a culture of prevention by enacting risk-based drought policies and plans combined with an early warning system. Building political capital means solving some of the multiple-stresses problems that impinge on the society and retard adaptation to drought. In addition, once drought mitigation actions have been implemented and specific impacts avoided or reduced, serious attention needs to be paid to lessons learned. This learning can then be fed back into the planning and early warning subsystems. The vulnerability-resilience continuum is considered in more detail in the next chapter.

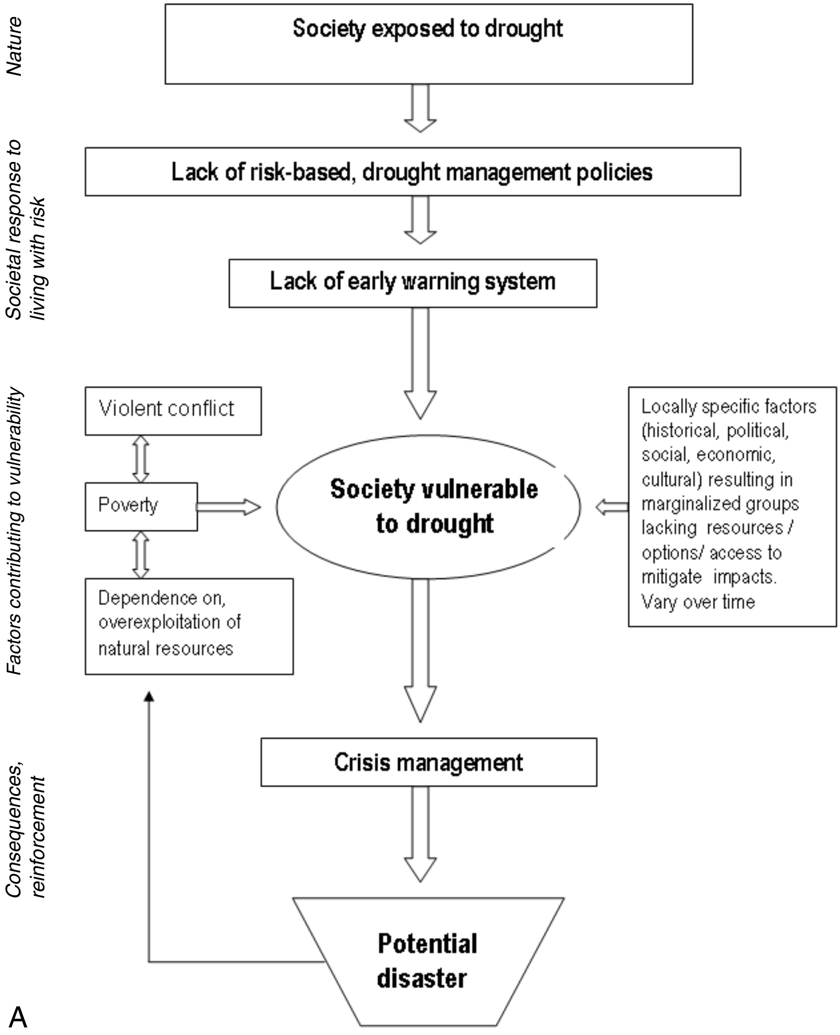
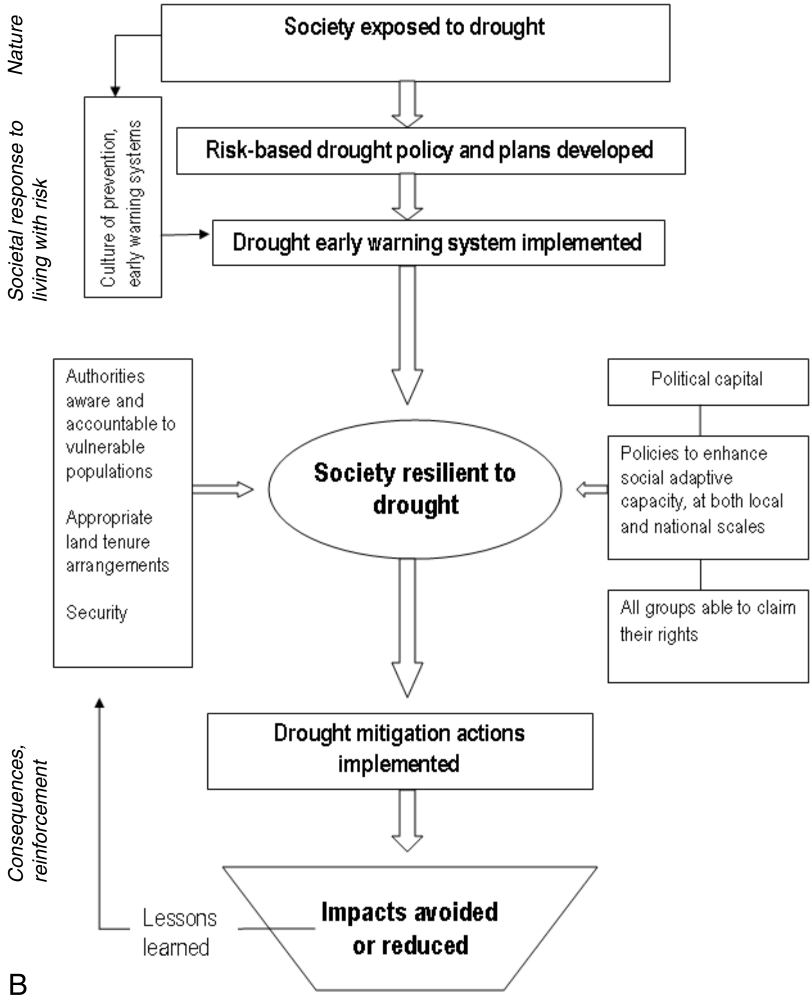


**FIGURE 1-1** Illustration of the difference between drought-vulnerable societies (A) and drought-resilient societies (B).
SOURCE: Wilhite and Buchanan-Smith (2005). Copyright 2005 from *Drought and Water Crises* by D. Wilhite, ed. Reproduced by permission of Routledge/Taylor & Francis Group, LLC. Modified from ISDR (2003).


Nature
Societal response to living with risk
Consequences, reinforcement
Society exposed to drought
Culture of prevention, early warning systems
Risk-based drought policy and plans developed
Drought early warning system implemented
Authorities aware and accountable to vulnerable populations
Appropriate land tenure arrangements
Security
Society resilient to drought
Political capital
Policies to enhance social adaptive capacity, at both local and national scales
All groups able to claim their rights
Drought mitigation actions implemented
Impacts avoided or reduced
Lessons learned
B

## BOX 1-1
## Key Definitions

***Adaptation:*** Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation.

***Adaptive capacity:*** The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

***Resilience:*** Amount of change a system can undergo without changing state.

***Sensitivity:*** Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

***Vulnerability:*** The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

SOURCE: IPCC (2001).

# 2

# Drought

There is no universal definition of drought. It has been defined in many ways by various disciplines because the characteristics of drought and its impacts reflect the climate and societal characteristics of the region affected. Conceptually, drought is a deficiency of precipitation from expected or "normal" conditions that extends over a season or longer period of time and where water is thus insufficient to meet the needs of human activities and the environment. Four types of drought are generally recognized: meteorological, agricultural, hydrological, and socioeconomic. Drought risk is a product of a region's exposure to natural hazards and its vulnerability to extended periods of water shortage. Drought is different from many other natural hazards in that it does not begin and end swiftly. Its onset is gradual, and as intensity and duration increase, the effects correspondingly become more widespread. This creeping phenomenon is expressed through multiple indicators because impacts are nonstructural and spread over large areas.

All meteorological droughts begin with a deficiency of precipitation over time. But nature is not the only cause of droughts. Droughts can be socially constructed or amplified when there is insufficient precipitation to meet needs (e.g., needs may be greater than "normal" supply if unsustainable development has occurred). Therefore, droughts are caused by changes in both supply of and demand for water, and both are dynamic. Impacts of drought are multifaceted. For instance, for agriculture, lack of precipitation affects the critical variables of soil moisture and evapotranspiration, and these become the vectors of adverse changes for society. For water supply for human uses, as the intensity, duration, and spatial extent of drought increase, the natural dimension decreases in

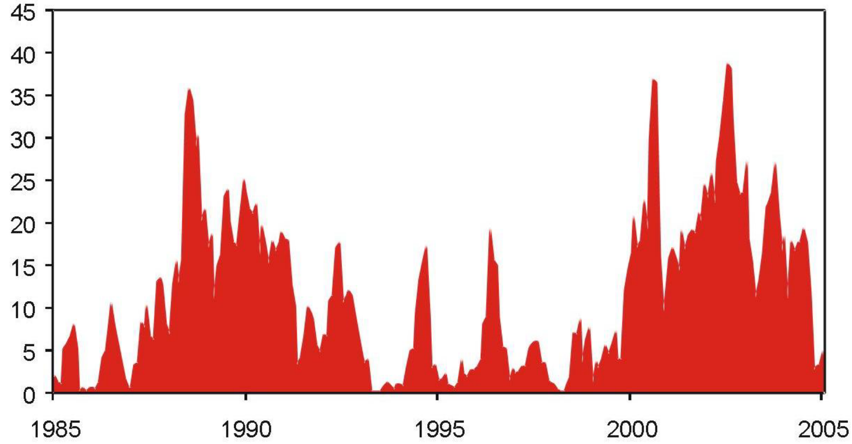


**FIGURE 2-1** Percent area of the United States in severe and extreme drought, January 1985-July 2005.
SOURCE: Based on data from the National Climatic Data Center/NOAA.

significance and a high priority is placed on water resources management. Some water shortages can be the result of overappropriation of supply so that "drought" occurs even in years of "normal" precipitation.

On average approximately 15 percent of the United States is affected by drought each year, based on the historical record from 1895 to now (National Climatic Data Center/NOAA, 2005). Figure 2-1 illustrates recent drought trends. Figure 2-2 illustrates longer-term trends for one location and shows a number of periods noteworthy for their duration, severity, and spatial extent.

A still ongoing drought began in 1996 for large parts of the country. Approximately 35 to 40 percent of the country has been affected at one time or another by severe to extreme drought during this period, and for some regions drought conditions have persisted for five or more years. For example, parts of the Southeast, particularly Georgia, North Carolina, South Carolina, and Florida, experienced three to four consecutive years of drought between 1999 and 2002. In the West much of the Southwest experienced five consecutive years of drought between 2001 and 2004, while much of Montana, Idaho, and surrounding states have experienced severe drought for as many as seven consecutive years since 1999. The most recent drought is particularly notable in that it was hotter than a similar drought of the 1950s. In general, western North America has seen significant warming over the last 100 years, particularly in the last couple of decades.

The recent period of unprecedented population increase in the western United States coincided with one of the wettest periods on record. During the

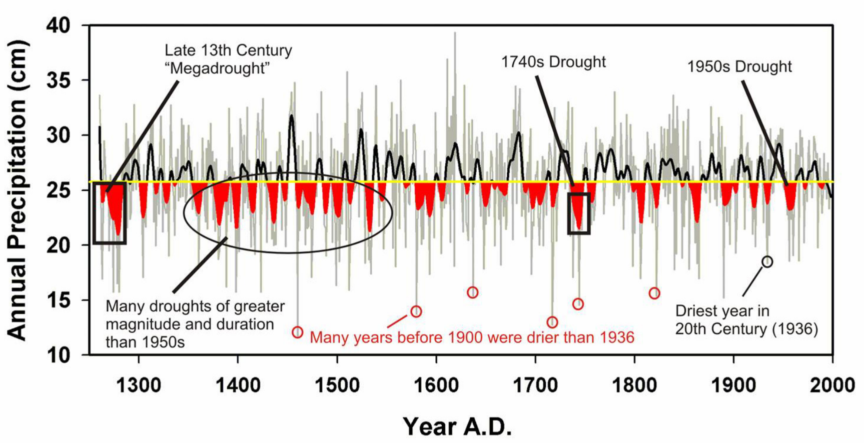


**FIGURE 2-2** Precipitation reconstruction for the Bighorn Basin, Wyoming/Montana. SOURCE: Compiled from data from Gray et al., 2004.

1990s, for example, the population of Nevada increased by 66 percent, Arizona by 40 percent, Colorado by 30 percent, Idaho by 28 percent, and New Mexico by 20 percent. The rapidly expanding population in the region is exacerbating water conflicts between multiple and competing users. It is also worth noting that the most important management agreement in the West (the Colorado River Compact of 1922) was based on an overestimation of the reliable average annual supply of water (estimated at 16.4 million acre feet [MAF] when the true long-term average flow of the Colorado River is estimated at between 12 and 16 MAF, with the current best estimate at 13.5 MAF) because the allocation was based on a short observational record that represented one of the region's wettest periods.[1]

The paleoclimate record, seen through proxy records such as tree rings, coral, and boreholes in ice, allows scientists to estimate precipitation amounts back much farther than the past few hundred years of instrument records, and it is clear that significant droughts are not solely a modern phenomenon (Cook et al., 2004; Woodhouse and Overpeck, 1998). Droughts comparable to those of the 1930s, 1950s, or early 2000s have occurred in general once or twice per century over the last 2000 years.[2] Research by Clark et al. (2002) using lake sediment records from

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[1] Connie Woodhouse, personal communication, June 6, 2006.

[2] Much of the material in this section is taken from the presentation of Dr. Jonathan Overpeck, University of Arizona, at the workshop, September 29-30, 2005.

the northern Great Plains shows pronounced 100- to 130-year drought cycles back at least 8,000 years.

Droughts of the 20th century were eclipsed by past droughts in terms of annual maximum severity, duration of drought, and geographic extent of drought. The paleoclimatic record indicates that droughts longer than a decade (i.e., "megadroughts") were not rare, and that droughts affecting much of the western United States have lasted as long as a century or more within the last 2,000 years (Gray et al., 2004). The true range of "natural" drought variability is thus substantially larger and more complex than suggested by the last century, when there are accurate records of drought variations provided by modern instrumentation.

In general, most of the large droughts of the western United States have affected more than one major river basin at a time, and some (e.g., a megadrought in the late 16th century) apparently affected the United States from coast to coast and from northern to southern borders. Another key aspect of drought variability illuminated by the paleoclimatic record is that decades- to centuries-long hydrological "regimes" (e.g., characterized by rare/short or frequent/longer droughts) have begun and ended abruptly; transitions between drought regimes can take place over years to decades, whereas the regimes themselves can be significantly longer.[3]

Great strides have been made in recent years with respect to understanding the proximal cause of drought in North America. Drought in the southwestern United States (e.g., 1950s and the recent drought) is known to be connected with the El Niño/Southern Oscillation (ENSO), and dry winters are favored in La Niña years.[4] More recently, studies have confirmed that anomalous sea surface temperature (SST) patterns, particularly in the tropics and the Indo-Pacific, can explain both 20th-century and earlier droughts, and research has identified strong statistical associations between decadal modes of Pacific and Atlantic variability with decadal patterns of wet and dry conditions over North America (McCabe et al., 2004; Hoerling and Kumar, 2003). Of course, the major challenge is to explain the causes of the anomalous—and persistent—ocean conditions that lead to North American drought.[5]

There is increasing consensus that anthropogenic forcing will likely increase the probability of drought in central and western North America.[6] Exacerbating this likelihood is the fact that temperatures are already rising significantly in the American West, and snowpack is retreating in the same region. A lesson of the paleoclimatic record is that anthropogenic forcing could trigger an abrupt transition into a more drought-prone climatic regime, thus increasing the frequency and duration of drought. Given that these possibilities could materialize with or with-

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[3] Jonathan Overpeck, presentation at the workshop, September 29-30, 2006.

[4] Ibid.

[5] Ibid.

[6] E.g., IPCC TAR,CLIVAR/PAGES/IPCC Workshop: A multi-millennia perspective on drought and implications for the future, November 18-21, 2003, Tucson, Arizona.

out significant future human-induced climate change, it makes sense to consider no-regrets strategies to reduce vulnerability to drought in either case.[7]

## CONTEXT AND IMPACTS

As noted earlier, drought was selected for examination as a case study because it both is driven by multiple environmental stresses and leads to multiple stresses across a wide range of scales. Drought is, at its simplest, an imbalance between water supply and water demand. Yet in reality, so many variables are present in both sides of that equation that it is clearly a classic example of a multiple-stresses scenario, where many factors combine in ways that are not entirely predictable. Drought typically evolves slowly, and as it progresses the impacts accumulate and expand in scope, extent, and intensity. From any one impact, there can be cascading impacts. This is clearly a challenge for decision makers who must plan for and react to the accumulating impacts.

Both climate and society are dynamic, as are the relationships between them (i.e., impacts and vulnerabilities). The different influences occur on varying scales (both time and space) and thus are challenging to predict with any accuracy. Drought is indeed a normal component of climate variability, but as a generator of multiple environmental stresses, it is the longer droughts—multiyear, multidecadal, and even centennial—that are of greatest concern. The longer the drought, the wider the range of ecosystem and societal effects that cascade from primary to tertiary impacts as time lengthens and spatial scales widen.

Terrestrial ecosystems respond not only to temperature but particularly to decreasing soil moisture that in turn induces woody plant mortality, rapid canopy change, and increased soil erosion.[8] Drought-induced tree mortality results in heightened vulnerability to fires. Note that canopy fires are the largest type of wildfire events in forests (Strauss et al., 1989). Increased temperature over long periods of time can also facilitate larger infestations of pests that magnify tree mortality and thereby expand the spatial scale of forest fires. Ecotones, or zones of transition between ecosystems, appear to be most susceptible to rapid vegetation change under stress (Allen and Breshears, 1998). As reductions in herbaceous groundcover increase, the distribution of near-ground energy is altered and can affect a wide range of ecosystem processes dependent on that energy. The threat of nonlinear increases in soil erosion rises significantly as a consequence of that shift in near-ground energy.

As drought intensifies over time, its spatial scale expands and its societal ramifications deepen (Wilhite et al., 2005). Infrastructures are affected, as is the supply of social services, and there emerge serious distributive consequences for the less well off members of society. Trends in the spatial distribution of water,

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[7] Jonathan Overpeck, presentation at the workshop, September 29-30, 2005.

[8] David Breshears, presentation at the workshop, September 29-30, 2005.

population size, demand, and competing uses all gain heightened significance and increased stress at times of increasing water scarcity.

Rates of change in the timing and supply of water, as well as sequencing of wet and dry years, can aggravate the impacts of drought. When wet and dry years can alternate frequently, human and ecological systems adapt to the extremes of variability; multiyear variability, on the other hand, presents the illusion of stability and the human impacts can be greater because people plan inadequately. Not only do human expectations differ based on timing and sequencing, but insects, pathogens, and other pests also respond in nonlinear fashion to some hydrological trends. Sequencing of water availability in the second half of the 20th century and into the first decade of the 21st century is of particular significance to the American West. For instance, snowpack provides up to 80 percent of the runoff, and since the 1950s there has been a long-term trend in increasing temperature and decreasing snowpack (Hamlet et al., 2005). The onset of spring and growing season evapotranspiration, the timing of snowmelt and snowmelt discharge, and the amount of recharge as the proportion of precipitation shifts from snow to rain at critical elevations will all have effects (Stewart et al., 2005; Cayan et al., 2001; Knowles et al., 2006). Increasing temperature, even if precipitation remains constant, has the potential to dramatically alter the hydrology of river basins and the severity of drought episodes. These types of trends are likely to lead to multiple stresses on both ecosystems and human social systems, thereby exacerbating competition between the two. Given these challenges, there is an acute need for further development of our capacity to predict the onset of drought. We now recognize that the true range of *natural* drought variability is substantially larger and more complex than is suggested by the 20th-century instrumental record. Research (Hoerling and Kumar, 2003) shows that while land surface feedbacks with the atmosphere can be important to amplify or dampen drought in some locations or seasons, these feedbacks are not always dominant in driving temporal drought variability, and patterns in coupled atmosphere-ocean variability also play an important role.

If the United States and other nations are to make progress in reducing the serious consequences of drought, an improved understanding of the hazard and its prediction and the full range of factors that influence vulnerability is needed. Enhancing our knowledge of the hazard will require a complex, integrated early warning system that incorporates climate, soil, and water supply factors such as precipitation, temperature, soil moisture, snowpack, reservoir and lake levels, groundwater levels, and streamflow. The implementation of the National Integrated Drought Information System (NIDIS), currently underway within the National Oceanic and Atmospheric Association (NOAA), represents a multiagency and multiorganizational effort and was viewed by workshop participants as an important step in the development of an improved decision-support system for the country.

Because of the slow-onset nature of drought, the ability of resource managers to adapt and/or impose alternative management practices in a timely fashion would be greatly enhanced by more reliable seasonal climate forecasts. Unfortunately, little skill currently exists to reliably predict the onset, severity, duration, spatial extent, or end of a drought event a season or more in advance. This is a critical research need. In addition to improved seasonal forecasts, there is need for improved methods of probability risk assessments that rely on reconstructions of past climates and account for climatic nonstationarity to calculate the occurrence and return probabilities of drought (Enfield and Cid-Serrano, forthcoming). Improving seasonal forecasts and their application will also require collaboration between scientists at research institutes, universities, and federal agencies. The primary end users of these forecasts need to be involved in this process so researchers understand their needs.

## UNDERSTANDING VULNERABILITY AND RESPONSE STRATEGIES

Vulnerability to drought is dynamic and is influenced by a multitude of factors, including increasing population, regional population shifts, urbanization, technology, government policies, land use and other natural resource management practices, desertification or land degradation processes, water use trends, and changes in environmental values (e.g., protection of wetlands or endangered species). Therefore, the magnitude of drought impacts may increase in the future as a result of an increased frequency of occurrence of the natural event (i.e., meteorological drought), changes in the factors that affect vulnerability, or a combination of these elements. The development of a national drought policy and preparedness plans at all levels of government that place emphasis on risk management rather than following the traditional approach of crisis management would be a prudent step for the United States to take. Crisis management decreases self-reliance and increases dependence on government and donors.

The impacts of drought in recent years have been increasing, although there is no systematic national assessment of drought impacts such as exists with other natural disasters. The Federal Emergency Management Agency (FEMA) (1995) estimated annual losses in the United States because of drought at $6 to $8 billion, making drought the most costly natural disaster in the country until Hurricane Katrina in 2005. Losses from the 1988 drought have been estimated at more than $39 billion. The National Drought Mitigation Center (Hayes et al., 2004) has estimated that the losses associated with the 2002 drought exceeded $10 billion, based on estimates made by 10 states. If these losses are extrapolated to include all drought-affected states, they would be significantly higher. It is important to note that these are estimates for a single drought year; major drought events often occur over a series of years (e.g., 1999-2005).

The impacts of drought have also been growing in complexity. Historically, the most significant impacts associated with drought have occurred in the agricultural sector (i.e., crop and livestock production). There has been an expansion of impacts in other sectors, particularly energy production, recreation and tourism, transportation, forest and wildland fires, urban water supply, environment, and human health. The recent drought years in the western United States, for example, have resulted in financial impacts in nonagricultural sectors that have likely exceeded those in agriculture. In addition to the direct impacts of drought, there are significant indirect impacts that, in many cases, exceed in value the direct losses associated with drought episodes. In addition to these human-focused impacts, there are the effects on nonhuman systems that are even more difficult to quantify.

## DROUGHT POLICY AND PREPAREDNESS

In the past decade or so drought policy and preparedness have received increasing attention from governments, international and regional organizations, and nongovernmental organizations. Simply stated, a national drought policy is a way to establish a clear set of principles or operating guidelines to govern the management of drought and its impacts. The ideal policy is consistent and equitable for all regions, population groups, and economic sectors and is consistent with the goals of sustainable development and the wise stewardship of natural resources. The overriding principle of drought policy is an emphasis on risk management through the application of *preparedness* and *mitigation* measures. Preparedness refers to predisaster activities designed to increase the level of readiness or improve operational and institutional capabilities for responding to a drought episode. Mitigation is short- and long-term actions, programs, or policies implemented during and in advance of drought that reduce the degree of risk to human life, property, and productive capacity. These actions are most effective if done before the event. Emergency response will always be a part of drought management because it is unlikely that government and others can anticipate, avoid, or reduce all potential impacts through mitigation programs. A future drought event may also exceed the capacity of a region to respond. However, emergency response is best used sparingly and only if it is consistent with longer-term drought policy goals and objectives.

A key component of a national drought policy is to reduce risk by developing better awareness and understanding of the drought hazard and the underlying causes of societal vulnerability (Hayes et al., 2004). The principles of risk management can be promoted by encouraging the improvement and application of seasonal and shorter-term forecasts, developing integrated monitoring and drought early warning systems and information delivery systems, developing preparedness plans at various levels of government, adopting mitigation actions and programs, and creating a safety net of emergency response programs that ensure timely and targeted relief. The delivery of information in a timely manner is essential so that informed decisions can be made by resource managers and others.

The traditional approach to drought management has been reactive, relying largely on crisis management. This approach has been ineffective because response is untimely, poorly coordinated, and poorly targeted to drought-stricken groups or areas. In addition, drought response is post-impact and relief tends to reinforce existing resource management practices (i.e., it rewards poor resource management and the lack of preparedness planning). Many governments are striving to learn how to employ proper risk management techniques to reduce societal vulnerability to drought and therefore lessen the impacts associated with future drought events.

There are four key components in an effective drought risk reduction strategy (O'Meagher et al., 2000): (1) the availability of timely and reliable information on which to base decisions; (2) policies and institutional arrangements that encourage assessment, communication, and application of that information; (3) a suite of appropriate risk management measures for decision makers; and (4) actions by decision makers that are effective and consistent. In 1992 Australia adopted a national drought policy that applied these components through three objectives: (1) to encourage primary producers and other sections of rural Australia to adopt self-reliant approaches to managing for climatic variability; (2) to maintain and protect Australia's agricultural and environmental resource base during periods of extreme climate stress; and (3) to ensure early recovery of agricultural and rural industries, consistent with long-term sustainable goals (O'Meagher et al., 2000). Australia's national drought policy is widely known and its philosophy adaptable in other settings (Botterill, 2005).

In the United States there has been some progress in the development of preparedness plans. The most noticeable progress has been at the state level, where the number of states with drought plans has increased dramatically during the past two decades. In 1982 only three states had drought plans in place; in 2005, 38 states had developed plans. The basic goal of state drought plans should be to improve the effectiveness of preparedness and response efforts by enhancing monitoring and early warning, risk and impact assessment, and mitigation and response. Plans should also contain provisions (i.e., an organizational structure or framework) to improve coordination within agencies of state government and between local and federal government. Initially, state drought plans largely focused on response efforts aimed at improving coordination and shortening response time; today the trend is for states to place greater emphasis on mitigation as the fundamental element of a drought plan. Thus, some plans are now more proactive, adopting a more risk management approach to drought management.

Drought mitigation plans have three essential components, regardless of whether they are developed at the state, national, regional, or local scale.

1. A comprehensive monitoring and early warning system provides the basis for many of the decisions that must be made by a wide range of decision makers as drought conditions evolve and become more severe. Equally important, early warning systems need to be coupled to an effective delivery system that disseminates timely and reliable information. As drought plans incorporate more mitigation actions, it is imperative that these actions be linked to thresholds (e.g., reservoir levels, climate index values) that can serve as triggers for mitigation and emergency response actions.
2. A critical step in the development of a mitigation plan is the conduct of a risk assessment of vulnerable population groups, economic sectors, and regions (Knutson et al., 1998). The purpose of the risk assessment is to determine who and what is at risk and why. This is accomplished through an analysis of historical and recent impacts associated with drought events.
3. After impacts have been identified and prioritized, the next step is to identify appropriate mitigation actions that can help to reduce the risk of each impact for future drought events.

One existing need is quantifying the advantages of a risk-based drought mitigation planning effort over the crisis management approach so policy makers see the advantages of committing resources up front to develop and implement mitigation actions rather than waiting to deal with impacts during a crisis. In most cases the costs associated with mitigation actions are minimal when compared with the costs of drought, which often are in the billions of dollars.

The U.S. Congress has considered actions that could be taken in response to recommendations issued in May 2000 by the National Drought Policy Commission (NDPC) but has not moved on these discussions. One of the NDPC's recommendations strongly endorses drought planning at all levels of government. Legislation has been introduced in the U.S. Congress that could lead to the creation of a more permanent national drought council and a national drought policy. Key components of this bill included an emphasis on risk management, preparedness planning, and improvement of the nation's drought monitoring system and forecasting capabilities. A project, the National Integrated Drought Information System (NIDIS),[9] is intended to provide the foundation for development of an improved drought monitoring system (Western Governors' Association, 2004). NIDIS is one of the components of the National Drought Preparedness Act, and authorization for NIDIS has been included in two bills introduced in Congress (HR 5136, S2751) in spring 2006.

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[9] *http://www.westgov.org/*.

## RESEARCH NEEDS

During the workshop, once the formal presentations were complete, the participants brainstormed a variety of possible research questions and needs. It was noted that the ability to make projections about the future is what makes knowledge powerful, and that in drought this means that much of the work is site specific and situation dependent. Because investment strategies related to water management and drought mitigation will differ depending on the size, cost, and service life of the strategy or facility, such projections are particularly important to policy makers. Integrated analysis of multiple stresses needs to replace cause-effect-type analysis. Much needs to be done to link large and small scales so that broad-based knowledge actually has practical application on the ground. There are still major gaps in understanding and communicating to and from the user community, and this inherently includes education and outreach. There is great value to studying the paleo record both because this gives us a basis for understanding megadrought and because looking at the past gives a greater time span over which relationships between duration, frequency, severity, extent, and location can be defined and quantified at the continental scale. There is also a need to consider the impacts on the services provided by ecosystems.

Finally, participants discussed possible steps to improve our capability to integrate science knowledge so that we are better able to deal with multiple stresses in decision support, with a focus on research needs. For the drought case study, the participants listed the following as steps that could advance our understanding of the multiple-stresses components and interactions for drought:

- Implement the National Integrated Drought Information System, emphasizing a partnership between federal and nonfederal agencies and organizations. This would improve monitoring and early warning systems to provide better and more timely and reliable information to decision makers; address data gaps in drought monitoring and enhance networks, particularly for soil moisture, snowpack, and groundwater; and develop new monitoring and assessment tools/products that will provide resource managers at all levels with proper decision-support tools at higher resolution.
- Help the scientific and policy communities and resource managers better understand drought as a complex natural hazard. For example, more effort could be made to communicate information on probabilities of single- and multiple-year drought events to natural resource managers and planners, policy makers, and the public in ways and formats that make sense to different audiences. Paleoclimate and historical climate research could be done to better understand past droughts at the regional scale. Additional research could be done on nonlinear processes and thresholds to provide improved prediction capability about the connections between tree mortality, energy and water budget shifts, and soil erosion.
- Improve the reliability of seasonal climate forecasts and train end users on how to apply this information to improve resource management decisions

with the goal of reducing drought risk. One part of this might be to develop more competitive research grant programs to fund research on drought prediction. In particular, there is a need for enhanced observations and research on both the paleoclimate record and the drought-related dynamics of ocean-atmosphere coupling. Another idea might be to form a consortium of scientists to encourage collaboration on drought prediction. New funding mechanisms might be needed that explicitly encourage multidisciplinary research bridging the gap between physical and biological science and human needs. Finally, it might be useful to develop a network of scientists and end users to assess the practical needs of end users and how forecast information can be communicated more effectively to the user community to maximize its application.

- Assess the economic, social, and environmental impacts associated with drought. Unless we improve our understanding of human behavior, the best intentioned plans will continue to produce less than desired results. The inadequate assessment of drought costs continues to be a significant problem in communicating the importance of drought mitigation to the management and policy communities. More accurate assessments of the true impacts of drought would provide greater justification for investments in mitigation actions at the local, state, and regional levels. Finally, work could be done to improve early assessments of drought impacts through the application of appropriate models (i.e., crop, hydrological).
- Assess the science and technology needs for improving drought planning, mitigation, and response at the local, state, tribal, regional, and national levels. To do this, it might be necessary to evaluate current drought planning models available to governments and other authorities for developing drought mitigation plans at the state and local levels of government and require plans to follow proposed standards or guidelines. Efforts could be made to identify improved triggers (i.e., links between climate/water supply indicators/indices and impacts) for the phase-in and phase-out of drought mitigation and response programs and actions during drought events. Work could be done to develop vulnerability profiles for various economic sectors, population groups, and regions and to identify appropriate mitigation actions for reducing vulnerability to drought for critical sectors.
- Increase awareness of drought, its impacts, trends in societal vulnerability, and the need for improved drought management. This might include initiating K-12 drought/water awareness programs/curricula or launching public awareness campaigns for adult audiences, directed at water conservation and the wise stewardship of natural resources.
- Design more focused and systematic education and outreach programs for stakeholders based on information derived from periodic surveys of their interests. From the results of such surveys, design workshops tailored to the specific interests of different combinations of stakeholders with the objective of producing decision-support tools on a continuing basis.

# 3

# Atmosphere-Ecosystem Interactions

The atmosphere and the earth's ecosystems are parts of a coupled system. For a large variety of processes, forcing from one partner in the interaction elicits one or more responses from the other partner, which in turn elicits other responses from the first. This bidirectional coupling gives atmosphere-ecosystem interactions the potential to be among the most complex in the natural world. The increasing involvement of human actions as important drivers introduces a broad new suite of responses and interactions. Historically, most of the study of drivers and responses in atmosphere-ecosystem interactions has started with single-factor investigations, building on the infrastructure, concepts, and tools of particular disciplines. Over the last several decades new knowledge has continued to accumulate in the traditional disciplines, but more and more of the breakthroughs are at the borders of traditional disciplines. Climate dynamics, hydrology, atmospheric chemistry, ecology, oceanography, and geomorphology function increasingly as a single superdiscipline, often called earth system science. In the future continued progress in this new superdiscipline is likely to require effective collaboration with or integration of a wide range of human sciences, from agronomy and civil engineering to economics and government.

The potential importance of bidirectional interactions is long acknowledged but relatively little studied, at least until recently. For example, Ahhrenius's calculations (1896) of climate forcing from coal combustion identified key components in anthropogenic warming, and in the 19th century the claim that rain follows the plow was a powerful inducement for agricultural expansion in the western United States. Following the introduction of climate models, insights on bidirectional coupling began to emerge. Studies by Charney et al. (1975, 1977) on the role of vegetation (or lack of vegetation) in modulating the climate of the Sahara are classic foundations for the modern science of atmosphere-ecosystem interactions. Later studies on the role of vegetation in the climate of the Amazon basin (Salati and Vose, 1984; Shukla et al., 1990; Dickinson and Henderson-Sellers, 1988; Lean and Warrilow, 1989) began to bring human actions into the science of atmosphere-ecosystem interactions. At about the same time, analyses of deforestation indicated its potentially large contribution to climate forcing through the carbon cycle (Woodwell et al., 1983). Also around this time a series of breakthroughs established the role of chemicals released from plants and from human processes in modulating the chemistry of the atmosphere (ozone hole, biogenic volatile organic components).

Since these early discoveries, understanding the nature and implications of atmosphere-ecosystem interactions has been one of the central goals in earth system science. It is also increasingly clear that understanding atmosphere-ecosystem interactions is one of the fundamental prerequisites for designing a path to a sustainable future.

## CONTEXT AND IMPACTS

The earth, oceans, atmosphere, and human actions need to be considered as a single, coupled system for a thorough understanding of climate, ecosystems, hydrology, or atmospheric chemistry. At small spatial and temporal scales, the coupling ceases to be of first-order importance. But at larger scales of space and time, the coupling between the atmosphere, land ecosystems, and oceans is always relevant and often dominant.

In the coupled earth system, components respond differently to different forcings. Responses are often nonlinear and often have threshold-type characteristics, with little response over a wide range of forcing, followed by a transition to a fundamentally new state over a short time or a narrow range of forcing. Understanding the locations of these thresholds and the mechanisms controlling them is among the most important challenges in earth system science. The lack of an obvious response to initial forcing can lead to the incorrect conclusion that a component of the system is insensitive to the altered environment.

Many of the behaviors of parts of the earth system have clear threshold responses. Wildfires, for example, almost never occur until temperature, humidity, fuel load, and fuel moisture enter the permissive range. But when all the environmental conditions are compatible with sustaining a wildfire, risks increase rapidly. This wildfire threshold could have important implications for Amazon rainforests if the future is warmer and drier (Nepstad et al., 1999). It could also interact in an important way with anthropogenic burning given the recent evidence that aerosols from Amazon fires can decrease rainfall (Andreae et al., 2004). And in a clear example of a feedback, reduced rainfall over tropical land masses during El Niño events has been shown to encourage more biomass burning in the tropics, which in turn yields higher annual concentrations of carbon dioxide ($CO_2$) in the atmosphere; knowing this could lead resource managers to greater policing in El Niño years in an attempt to reduce the extent of burning by agriculturalists and reduce carbon emission.

Other important examples of threshold come from the response of temperate forest ecosystems to warming or the deposition of atmospheric nitrogen. In controlled ecosystem experiments nitrogen inputs produce little change over several years, but the nitrogen excess eventually reaches a point where the system collapses.[1] In response to warming the initial response is a large increase in soil warming, followed by a sudden decline when the ecosystem runs out of easily decomposable material.[2]

Some of the important thresholds in earth system responses can operate in more than one direction. One good example of this is the relationship of atmospheric ozone to levels of volatile organic compounds (VOCs) in the atmosphere. Depending on the ratio of VOCs to nitrogen oxides ($NO_x$), an increase in VOCs could lead to a large decrease or a large increase in ozone production.[3] Changes in land use can behave as thresholds.[4] Often, dramatic changes in land use follow changes in policy, price supports, or transportation infrastructure. If consequent changes in local climate make the changes in land use difficult to reverse (Dickinson and Henderson-Sellers, 1988; Lean and Warrilow, 1989; Shukla et al., 1990), the changes that occur across a narrow threshold can be locked in place.

Interactions between the earth, oceans, and atmosphere often involve the simultaneous action of diverse mechanisms. Terrestrial and ocean carbon balance provide beautiful examples of the overall fluxes controlled by a large number of individual mechanisms. In the oceans, temperature interacts with alkalinity, salinity, and dissolved inorganic carbon to control $CO_2$ solubility (Sabine et al., 2004). Biological processes are also important contributors to the carbon balance of the oceans, with potentially subtle changes in the composition of the producer and consumer communities leading to substantial effects on the downward transport of particulate carbon (Sabine et al., 2004). On longer timescales the delivery of mineral nutrients from upwelling or from the delivery of windborne dust plays an important role.

On land, diverse processes contribute to the overall carbon balance (Pacala et al., 2001). The current carbon balance of the United States has large influences due to land use change, $CO_2$ fertilization, nitrogen deposition, ozone, and climate.[5] The early optimism that future terrestrial carbon dynamics might be modeled as a simple response to atmospheric $CO_2$ (Bacastow and Keeling, 1973) has been replaced by an appreciation that drivers from human actions,

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[1] Jerry Melillo, presentation at the workshop, September 29-30, 2005.

[2] Ibid.

[3] Alex Guenther, presentation at the workshop, September 29-30, 2005.

[4] Patricia Romero-Lankao, presentation at the workshop, September 29-30, 2005.

[5] Jerry Melillo, presentation at the workshop, September 29-30, 2005.

atmospheric composition, climate, and ecological processes all interact, with contrasting relative importances in different settings.

Climate change is expected to influence the capacities of the land and oceans to act as repositories for anthropogenic carbon dioxide and in turn provide a feedback that affects climate further. Modeling experiments show that carbon sink strengths vary with the rate of fossil fuel emissions, so carbon storage capacities of both land and oceans decrease and climate warming increases with faster emissions (Fung et al., 2005).

The bidirectional nature of earth-atmosphere interactions has important implications for a wide range of earth system processes. Coupling plays a central role in both carbon-climate and climate-albedo feedbacks. Many experiments and simulations indicate that, depending on the starting point, a warmer climate can lead to either a loss or gain of ecosystem carbon[6,7] (Mack et al., 2004; Shaver, et al., 2006). If in response to warming, ecosystems lose carbon, then atmospheric carbon increases, producing a positive feedback on the initial warming. If warming leads to an increase in ecosystem carbon (with more carbon in plants and soils), then the feedback is negative. A number of model experiments now explore the role of land and ocean feedbacks in modulating the climate forcing from atmospheric $CO_2$. The general conclusion from these studies is that the terrestrial feedback is positive (in the direction of exaggerating warming)[8] (Cox et al., 2000; Friedlingstein, 2004; Fung et al., 2005), although the magnitude of the feedback is uncertain. The $CO_2$ sensitivity of the climate model used in these simulations plays an important role in determining the strength of the feedback, as does the tendency of the ocean to take up the carbon released from the land. The magnitude of the current uncertainty is large. With comparable forcing from anthropogenic $CO_2$ emissions, equally credible models end the 21st century with atmospheric $CO_2$ levels differing by more than 200 ppm, a quantity of $CO_2$ greater than the total released by fossil fuel combustion to date.

Albedo-climate feedbacks may be equally important. New evidence indicates that warming in the Arctic is already leading to increased abundances of shrubs, which lead to an increase in the absorption of solar radiation, especially in the spring, and reinforce the warming (Chapin et al., 2005). Simulation results indicate that historical land use in the central United States has cooled the climate. The lack of historical cooling reflects the combined effects of this albedo effect, plus other processes that have counteracted it. Combining effects on albedo and carbon storage, increasing forest biomass in the temperate latitudes tends to produce a net warming, while reforestation or afforestation in the tropics tends to produce a net cooling (Gibbard et al., 2005).

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[6] Ibid.

[7] Scott Doney, presentation at the workshop, September 29-30, 2005.

[8] Ibid.

Humans exert and respond to a wide range of stresses in the coupled earth-ocean-atmosphere system. Almost all studies of natural science components of global change considered human drivers as a fixed set of boundary conditions, and analyses of human responses viewed changes in climate or air quality as givens. While these are clearly simplifications, research teams simply did not have the breadth of expertise or the technical tools to tackle truly integrated approaches. A few teams have recently made bold attempts to integrate human actions and the natural sciences in an interactive framework. For example, the scenarios developed for the Millennium Ecosystem Assessment use a modeling framework that attempts to integrate changes in agricultural demand with changes in climate, leading to, among other things, projections of deforestation and prices of major agricultural crops (MEA, 2005). Recent Massachusetts Institute of Technology Emissions Prediction and Policy Analysis simulations address interactions among climate, ozone, crops, and the economy in a coupled framework.[9] They have also looked at air pollution, human health, and the economy as a coupled system. Consistent with the early stage of this research, many of the potentially most important drivers of change in patterns of human action have not been explored with coupled models. Specifically, the impacts of HIV/AIDS and other major epidemics could have major impacts on future human activity.[10] The fundamentally important distribution of wealth, opportunity, and independent decision making[11] was a focus of the Millennium Ecosystem Assessment,[12] but its exploration with coupled models is just beginning.

Clearly, atmosphere-ecosystem interactions unfold through diverse processes, across a range of scales, and with nonlinearities. We have some understanding of a variety of the mechanisms involved, but there are many uncertainties. Much uncertainty relates to the impacts of global change on humans, ecosystems, and economies; interactive effects among these sectors have the potential to amplify or suppress the initial effects, sometimes by a large multiplier. As with the drought case study, this is a scenario where varied impacts can accumulate and expand in scope, extent, and intensity. From one impact there can be cascading impacts.

## IMPACTS ON HUMANS, ECOSYSTEMS, AND ECONOMIES

Atmosphere-ecosystem interactions unfold through diverse processes. Climate, air pollution, droughts, and fires are all sensitive to controlling mechanisms that have atmospheric components, ecosystem components, and components that arise specifically from the interactions between them. Though most of these

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[9] John Reilly, presentation at the workshop, September 29-30, 2005.

[10] William Easterling, presentation at the workshop, September 29-30, 2005.

[11] Patricia Romero-Lankao, presentation at the workshop, September 29-30, 2005.

[12] Harold Mooney, presentation at the workshop, September 29-30, 2005.

mechanisms are understood in outline form, many of the details are unknown. Much of the reason that the range of uncertainty related to impacts of global changes on humans, ecosystems, and the economy is so large is that the interactive effects have the potential to amplify or suppress the initial effects, sometimes by a large multiplier.

Several kinds of human factors can exaggerate vulnerability to the impacts modulated by atmosphere-ecosystem interactions. Poverty, lack of control over one's destiny, and an extremely unequal distribution of wealth all tend to decrease coping capacity, increase vulnerability, degrade ecosystem services, and increase the challenge of finding effective paths toward solutions.[13] In contrast, human factors that stimulate technical innovation, distribute control, and encourage local decision making can decrease vulnerability while increasing ecosystem services.[14]

Atmosphere-ecosystem interactions introduce potentially important uncertainties into a large suite of future global changes. Characterizing these uncertainties and, where possible, reducing them, is one of the central challenges of global change research. Still, it is important to recognize that unknowns in the realm of human actions increase the uncertainties even further.[15] For a truly useful understanding of the range of global change processes, we need to develop useful ways to more effectively integrate earth, atmospheric, and human processes.[16]

## POLICY OPTIONS: ADAPTATION AND MITIGATION

Atmosphere-ecosystem interactions have important impacts not because they result in new phenomena but because they modulate a wide range of earth and atmospheric processes. Especially in a context with multiple, simultaneous interaction drivers, this modulation can be of primary importance. Atmosphere-ecosystem interactions have the potential to amplify the impacts of minor processes or suppress the impacts of major ones. They are the dominant sources of uncertainty in some processes and a major source of uncertainty in others. Increased understanding of these interactions is a major theme in global change research.

In many settings increased understanding of atmosphere-ecosystem interaction can play a central role in designing effective strategies for adapting to or mitigating impacts of global change. A central need is a thorough enough understanding of these interactions to map the locations of thresholds, especially those that cause positive feedbacks in global change responses. Examples of threshold responses in these interactions are increasingly well developed. For instance, it

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[13] Ibid.

[14] Ibid.

[15] Patricia Romero-Lankao, presentation at the workshop, September 29-30, 2005.

[16] Harold Mooney, presentation at the workshop, September 29-30, 2005.

is well known that warming that leads to increases in the abundance of Arctic shrubs, which when the shrubs become common enough, decreases local albedo and amplifies warming (Chapin et al., 2005). Another example is the effect of nitrogen fertilization. While increasing deposition of reactive nitrogen (typically as $NO_3$ and $NH_4$+) can lead to increased uptake of $CO_2$, nitrogen fertilization typically also results in emissions of nitrogen gasses (e.g., $NH_3$ and $N_2O$, an even more powerful greenhouse gas than $CO_2$) (e.g., Vitousek et al., 1997). Also, nitrogen fertilization leading to nitrogen saturation of terrestrial ecosystems results in the loss of nutrient cations, causing reduced productivity locally and eutrophication of aquatic systems downstream (Vitousek et al., 1997). Interactions can also be multistep. For example, the effect of biogenic volatile organic carbon on tropospheric ozone can lead to an indirect impact of high temperatures on crop yields and forest growth.[17] The negative effects of elevated ozone are, somewhat surprisingly, not suppressed by growing trees in elevated $CO_2$ (Karnosky et al., 1999).

In some cases a thorough understanding of atmosphere-ecosystem interactions can provide an insurance policy against adaptations that fail to accomplish their goals or that have undesirable side effects. For example, recent evidence shows that especially in midlatitude forests the warming caused by decreased albedo can be larger than cooling from carbon storage, providing an important caveat in the motivation for broad reforestation efforts in the midlatitudes (Gibbard et al., 2005; Feddema et al., 2005).

In other cases an atmosphere-ecosystem interaction can serve as an effective foundation for successful mitigations even if they are unintentional. Increases in plant growth and ecosystem carbon in response to elevated atmospheric $CO_2$ (Prentice et al., 2001) provide a classical example of negative feedback on atmospheric carbon (see Figure 3-1). Another example concerns the possibility that an ocean acidified enough, in response to high atmospheric $CO_2$, to start dissolving carbonate may dramatically increase its rate of $CO_2$ uptake (Sabine et al., 2004).

In sum, atmosphere-ecosystem interactions do not establish a single set of issues for adaptation and mitigation. Instead, they appear almost as a large suite of risks and opportunities. Positive feedbacks have the potential to increase vulnerability, especially when responses cross thresholds. Negative responses have the potential to amplify the utility of adaptation and mitigation measures. In general, thorough understanding is critical, as the nature, direction, and magnitude of likely feedbacks are rarely clear.

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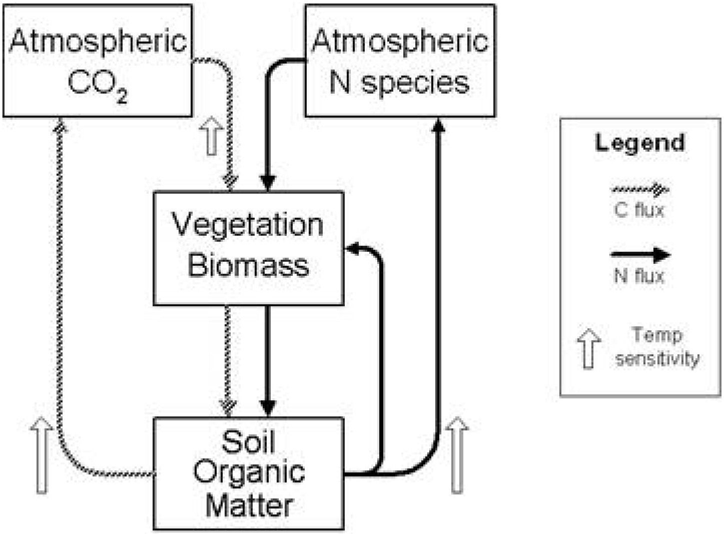
[17] Alex Guenther, presentation at the workshop, September 29-30, 2005.



**Coupled Carbon-Nitrogen Dynamics**

**FIGURE 3-1** There is a strong feedback between decomposition and plant growth, and soil mineral nitrogen is the primary source of nitrogen for plant growth. This can result in a shift from being a carbon source to carbon sink under warming.
SOURCE: Scott Doney, presentation at the workshop, September 29-30, 2006.

## RESEARCH NEEDS

The literature is increasingly rich with examples of important atmosphere-ecosystem interactions, but few, if any, are thoroughly understood. The community with the expertise to address questions in atmosphere-ecosystem interactions is small. Investigators in this area need to combine a research-level understanding of atmospheric processes with a sophisticated knowledge of terrestrial and marine ecosystems. For investigators not equipped to tackle the coupled system, collaborations are an essential tool, though interdisciplinary collaborations are often difficult and complex. Because some of the interactions unfold only on long timescales or large spatial scales, we need experimental, observational, and simulation techniques to explore the range of possibilities. This kind of work will require multifactor experiments.

From the workshop discussions participants identified the following interactions that could benefit from increased multifactor research. Participants noted that for most of these questions, key elements of a comprehensive understanding are in place, but resources for thorough study have been lacking. These items are not prioritized or necessarily similar in scope but rather reflect the workshop participants' on-site thinking.

- How do $CO_2$ and a warming climate interact to affect soil moisture, ocean acidification, and the carbon balance of ecosystems (both terrestrial and marine)?
- What is the role of biogenic VOCs in generating ozone, and what is the role of ozone in degrading crop yields?
- What is the role of changes in surface albedo in changing climate? What are the carbon-cycle implications of this?
- What is the role of air pollutants in degrading crop yields? How do these effects change with warming?
- How might human pressures for increased food production lead to an expansion of agricultural land, and what are the costs in ecosystem services for the converted land?
- How do human decisions about cropping, land use or cover change, and urbanization influence atmosphere-ecosystem interactions?
- How do greenhouse gas increases and associated warming, land use, and air pollution interact with biodiversity?
- What is the relative role of extreme events and average conditions in establishing the impacts of atmosphere-ecosystem interactions? Under what conditions do atmosphere-ecosystem interactions enhance the value of investments in adaptation and mitigation?
- How do drivers relate with stresses to produce certain vulnerabilities/adaptive capacities?
- How do socioeconomic, institutional, and environmental processes influence environmental change and adaptive capacity (livelihoods, migration)?
- How does information get to those who need it? What kinds of information are most useful to decision makers, resource managers, and others who could benefit?
- How can we develop improved tools and strategies for addressing multiple environmental stresses, such as improved observational and modeling capabilities, integrated sensors, regional information systems, and predictive capabilities?
- How can societal resilience to multiple environmental stresses be improved? How can adaptive management approaches be developed and implemented?

# 4

# Lessons Learned from the Case Studies

This workshop looked at two case examples, using presentations and discussion, to explore current understanding of multiple environmental stresses in the earth system and to discuss the types of research needed to improve integrated understanding of these kinds of complex, nonlinear problems. Understanding multiple stresses is challenging because it almost always requires consideration of multiple variables and larger, more complex spatial scales. Yet without a more sophisticated understanding of the impacts of a suite of environmental stresses, we cannot make the kind of progress necessary to improve our predictive capability and response strategies.

The overarching lesson of the workshop discussions is that a thorough understanding of the integrated effects of—and future vulnerability to—multiple stresses to natural and socioeconomic systems requires improved use of existing tools and strategies and, in addition, the development of improved tools and strategies—such as observational, modeling, and information systems infrastructure—to support environmental monitoring, vulnerability assessment, and response analysis and that the entire process needs significant involvement of stakeholders.

During the workshop, the National Ecological Observing Network[1] (NEON) was mentioned as an example of the type of nationally networked research, communication, and informatics infrastructure needed to provide more comprehensive and interdisciplinary measurements and experiments. References were also made to other possible infrastructure, such as

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[1] *http://www.neoninc.org/.*

- the National Phenology Network[2] (USA-NPN), designed to facilitate systematic collection and free dissemination of phenological data from across the United States to support research concerning interactions among plants, animals, and the lower atmosphere, especially the long-term impacts of climate change;
- the Ocean Research Interactive Observatory Networks[3] (ORION), designed to provide high-frequency, continuous time-series measurements in broad-scale spatial arrays needed to define the links among physical, biological, chemical, and geological variables in the oceans and provide spatially coherent data to study processes and enable modeling efforts;
- the Ameri-Flux Network,[4] designed to provide continuous observations of ecosystem-level exchanges of $CO_2$, $H_2O$, energy, and momentum spanning diurnal, synoptic, seasonal, and interannual timescales;
- the proposed Integrated and Sustained Ocean Observing System[5] (IOOS);
- the International Global Ocean Observing System[6] (GOOS); and
- the Global Earth Observation System of Systems[7] (GEOSS).

Observing systems alone cannot solve the puzzle of understanding multistress environmental problems, but they are a necessary component because they provide the data needed to characterize the environment and determine trends. There is a real need for careful attention to the systematic creation and validation of long-term, consistent climate data records (NRC, 2004a). The following paragraphs describe some of the other tools and strategies highlighted during the workshop.

## COMPREHENSIVE REGIONAL FRAMEWORKS

Many participants advocated development of comprehensive regional frameworks for environmental studies as outlined during the workshop's keynote address by Dr. Eric Barron. The vision Dr. Barron proposed included

1. an integrated regional web of sensors that link existing observations into a coherent framework and enable new observations to be developed within an overall structure;
2. an integrated and comprehensive regional information system accessible to a wide variety of researchers, operational systems, and stakeholders;
3. directed process studies designed to examine specific phenomena through field study to address deficiencies in understanding;

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[2] *http://www.uwm.edu/Dept/Geography/npn/.*

[3] *http://www.orionprogram.org/.*

[4] *http://public.ornl.gov/ameriflux/.*

[5] *http://www.ocean.us/.*

[6] *http://www.ioc-goos.org/.*

[7] *http://www.earthobservations.org/.*

4. a regional, high-resolution modeling foundation for constructing increasingly complex coupled system models at the spatial and temporal scales appropriate for the examination of specific and integrated biological, hydrological, and socioeconomic systems; and
5. a strong connection to significant regional issues and stakeholders.

Workshop participants returned repeatedly to the Regional Integrated Sciences and Assessments (RISA)[8] program as a possible model for such regional frameworks. (RISAs are discussed in greater detail later in this chapter.)

## A WEB OF INTEGRATED SENSORS

Current U.S. observation strategy tends to focus on the measurement of discrete variables at a specific set of locations designed to serve the different needs of weather forecasting, pollution monitoring, hydrological forecasting, or other specific mission objectives. This mission focus results in a diverse set of networks supported by a number of different federal agencies, states, or regional governments. A host of environmental issues motivates additional new observations. However, these new observations are frequently viewed independently of an integrated observing strategy. In addition, it is difficult to identify sufficient financial support for regular and consistently repeated observations. These factors severely limit our ability to integrate physical, biological, chemical, and human systems.

Creating comprehensive regional observing networks would allow us to (a) link observing systems into a web of integrated sensors building upon existing weather and hydrological stations and remote sensing capability; (b) create the agreements across a set of more limited agencies and federal, state, and local governments needed to create a structure to the observing system; (c) provide a compelling framework that encourages or demands the integration of new observations into a broader strategy; and (d) create strong linkages between research and operational observations that result in mutual benefit. Clearly, these steps will be difficult to achieve given political dynamics and constrained budgets, but these sorts of comprehensive approaches are needed to improve our capability to respond and ensure flexibility over time. The importance of continued support for and maintenance of existing environmental networks should not be underestimated as a foundation for what needs to happen in the future.

## REGIONAL INFORMATION SYSTEMS

Efforts to create comprehensive information systems increasingly reflect federal and state mandates to make data more accessible and useful to the public

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[8] *http://www.climate.noaa.gov/cpo_pa/risa/.*

and to ensure that our investments in research yield maximum societal benefit. Development of a tractable regional digital database is feasible and enables participation of universities; federal, state, and local governments; and industry in an endeavor for which immediate benefit for a state or region can be evident. For this to happen efficiently these information systems will need to take advantage of existing facilities and infrastructure, augmenting selectively as needed and, overall, improving the connections that bind the pieces together. This will take careful and detailed planning and a strong commitment to implementation.

## FRAMEWORK FOR PROCESS STUDIES

Process studies are a critical element of scientific advancement because they are designed to probe uncertainties in knowledge about how the earth system functions. The objective is to use field study to address deficiencies in our understanding. Targeted process studies improve our ability to quantify thresholds, understand nonlinear interactions of multiple environmental factors, and decipher long timescale responses to climate change. The benefit of these intensive studies is maximized when they can be coupled with a highly developed, integrated set of sensors, with readily accessible spatial and temporal data within a regional information system, and with a predictive model framework that readily enables the entrainment and testing of new information from process studies.

## IMPROVING OUR PREDICTIVE CAPABILITY

Prediction is central to the translation of knowledge about the earth system into economic benefit and societal well-being. Although there is still substantial room for improvement, over the last several decades we have experienced enormous increases in our ability to forecast weather and to project climate and climate variability into the future. The demand for new forecasting products involving air quality, energy demand, water quality and quantity, ultraviolet radiation, and human health indexes is growing rapidly. Environmental issues will demand an even greater capability to integrate physical, biological, chemical, and human systems in order to examine the response of critical regions or cases to multiple stresses.

Global weather and climate models provide the strongest physical foundation for more comprehensive predictive capability. The numerical models that underpin this type of forecast are increasingly becoming the framework for the addition of new numerical formulations designed to predict air quality, the water balance for river forecast models, and a host of other variables, including the migration of forests under climate change conditions. As we attempt to produce predictions at the scale of human endeavors, mesoscale models (capable of predicting synoptic weather systems) and downscaling of coarser resolution model output are increasingly becoming the focal point of weather and climate studies because of their

## BOX 4-1
## Examples of Tools and Strategies

After both cases were presented and discussed, workshop participants took part in brainstorming to identify examples of important observations, modeling tools, and research strategies for improving understanding of and response to multiple-stresses problems. This box captures those ideas to illustrate the range of possible actions; they are listed as presented and not prioritized or standardized in style or scope.

### *Observations*

- Maintain existing environmental networks and expand observing infrastructure (e.g., NEON) while maintaining a balance between high-cost, large platforms/instruments and low-cost, small platforms/instruments.
- Expand aircraft fleet to include smaller/lower cost aircraft. Consider using remotely piloted vehicles.
- Expand use of observing systems (flux towers and aircraft transects) for measuring net ecosystem exchange and developing/testing models.
- Expand use of remote sensing (satellite or aircraft) to access the increasing suite of ecological measurements and molecular biology tools.
- Focus on intersections and gradients.
- Expand field manipulations to develop process understanding; generate a plan for manipulation study priorities.
- Generate the capability to manipulate multiple variables and conduct experiments over appropriate spatial and temporal scales.
- Ensure consistency of long-term measurements because long-term data are needed to identify nonlinearities.
- Generate integrated, accessible data archive/information systems.
- Generate global databases of multiple stresses (georeferenced) for large-scale models; include a database of spatial economic data.

### *Models*

- Integrated hierarchy of models.
- Models that integrate human and natural components to study nonlinearities and thresholds.
- Extend model focus to effects on ecosystem trophic levels.
- Use ensemble runs to assess uncertainty and probability.
- Use inverse modeling to test end products of complex models.
- Station-specific data projection model based on historical information with the ability to perturb the model using appropriate climate forcing functions.
- Statistical tools that clearly display the interaction between data and forecast procedures and forecast validation.
- Develop model scenarios that provide better understanding of catastrophic events (e.g., war, pests, disease).

*continued*

### BOX 4-1 Continued

***Strategies***

- Integrate datasets and provide information delivery system to users.
- Map multiple stresses using multiple overlays in geographic information systems (GISs) to identify "critical zones."
- Create reliable indexes of leading vulnerability indicators that combine suites of stressors that are known to interact and might give a first-order monitoring capability (i.e., a Dow Jones-type index for the environment as a publicity tool).
- Use video/computer games as a multiple-stresses decision-support tool (e.g., use place-based scenarios to explore megadrought thresholds, drought scenarios, ocean or atmosphere scenarios).
- Make better use of existing data, such as by linking qualitative and quantitative information in impact assessments, expanding use of spatial representation (GIS) to visualize data, and improving decision analysis and understanding of uncertainties.
- Co-develop scenarios with those who use the information for decision making, working together in effective partnerships.
- Work with stakeholders at the design point so that research meets user needs.
- Work to better communicate risks.
- Use seemingly simple systems that exhibit complicated behavior that could be used by managers to illustrate probabilities (e.g., flood frequency analysis).
- Develop better models for drought planning, improve tools for municipalities, and generate methods for testing drought plans.
- Identify implications of changes in states or processes.
- Survey to identify ecosystem shifts/state changes/changing carbon or moisture levels (look to see if they do go through thresholds).
- Prioritize wetlands protection.
- Use regional monies to leverage efforts.

potential to make predictions on the scale of river systems, cities, agriculture, and forestry. Development of a mesoscale numerical prediction capability that meshes with regional sensor webs and information systems would facilitate development of tractable coupled models, initiate experimental forecasts of new variables, and enable assessment of the outcomes associated with multiple stresses.

## RESEARCH NEEDS RELATED TO NONLINEARITIES AND THRESHOLDS

Workshop participants frequently highlighted lessons learned about nonlinearities in the climate system and the difficulties associated with quantifying the effects of multiple interacting stresses and technological change. Although current models are useful in identifying single-variable nonlinearities, few models are sufficiently comprehensive to provide quantitative predictions of the effects of multiple environmental stresses. While coupled modeling systems developed in the future are expected to be useful in the identification of nonlinearities, it was thought that nonlinearities are currently best identified by long-term observations.

The thresholds considered by participants to have the highest priority for study include climate/pest interactions resulting in changes in functional types of natural vegetation; megadrought (climate threshold, ecosystem thresholds, human thresholds, cascading effects); and interaction between ecosystems, climate change, and air pollution. Suggestions regarding how best to approach the study of thresholds included studies involving initial system observations followed by single-variable and multiple environmental stresses experiments and modeling; studies focused on ecotones, zones where marginality of nutrients, predators, climate, land use, economics, and policies create unstable land uses that are especially sensitive to small variations in drivers; and studies of extreme conditions (e.g., air pollution in megacities) where changes in state may be observed. Participants also encouraged development of threshold typology, identification of a core set of controlling (and dynamic) variables that determine system behavior, assessment of the interaction of fast and slow variables (as related to the threshold); assessment of the degree to which a system may be capable of self-organization; and assessment of the ability to build and increase the capacity for learning and adaptation. Threshold-focused research needs to study both direct and indirect effects, linking thresholds and impact occurrence to indicators/indices, study of the full probability space of observations and model outputs, and consideration of new opportunities that are likely to result from globalization.

## RESEARCH NEEDS RELATED TO INCREASING RESILIENCE

Workshop participants encouraged the following approaches to increasing resilience to multiple environmental stresses:

- use of models;
- improvement of models for response planning;
- identification of additional water storage;
- consideration of new conservation strategies;
- maintenance of biodiversity;
- improved communication of environmental capacities and limitations to local officials;
- improved understanding of adaptive or buffering capacity, which is determined by the types of capital available (natural, social, human, cultural, and produced);

- full leveraging of adaptive capacity, technological capacity, and expertise;
- in-parallel focus on combinations of social and environmental stresses and combinations of environmental stresses;
- use of war games as a scenario-based tool for informing decision making, examination of historical analogs that share important similarities with contemporary (and anticipated future) stresses;
- incorporation of "normal" (rather than fair to good) socioeconomic conditions and civil and regional wars in scenarios for sustainable development; and
- linking results of models to resilience, improvement of public awareness of related issues, and elimination of nonsustaining financial incentives.

Moreover, a number of steps were suggested for the creation of vigorous and continuous links between researchers and decision makers, including

- incorporation of the variety of time and space scales and the diversity of variables that are important to decision makers;
- emphasis on the education of the user in the meaning and significance of climate and land use information in order to promote greater use and more robust applications;
- ensuring mutual information exchange and feedback;
- focus on communication and accessibility of information;
- continuous evaluation and assessment of the use and effectiveness of the services;
- employment of active mechanisms to enable the transition from research discovery to useful products; and
- employment of a variety of methods of education and outreach.

## RESEARCH NEEDS RELATED TO REGIONAL STUDIES

During the workshop the argument was made that the ability to anticipate the future is what makes knowledge powerful. The knowledge we seek concerns the role and effects of multiple stresses in the context of atmosphere-ecosystem interactions. These interactions include climate variability and change over a wide range of time/space scales, land use/land cover changes, human social systems, waste products and streams, and the combined effects of all the above on natural ecosystems. This knowledge must perforce be place based (i.e., site or region specific) because context is important. Integrated assessments of multiple stresses across a variety of time/space scales are required in which the impacts and decisions are place based but the drivers of impacts are drawn from a much larger scale. We can summarize by saying it is critical to link the large-scale drivers to place-based contexts with a focus on multiple stressors and put the knowledge to work—that is, connect in partnerships with real stakeholders and decision makers from the place where the work is done.

Obstacles to realizing the vision above include lack of the following:

- integrated observing systems;
- a common modeling framework;
- a foundation of process studies geared toward prediction;
- an integrated data and information system; and
- systematic, vigorous connections to real users of the information and decision makers.

One program in existence comes close to meeting the challenge described above and that is the Regional Integrated Sciences and Assessments (RISA) program of NOAA's Office of Global Programs. As described at the workshop, the RISA program was launched in 1995 with a pilot project at the University of Washington (the Climate Impacts Group). The program now consists of eight regional teams distributed across the United States, each with a focus on the role of climate variability and the projected impacts of climate change in defined sectors of human socioeconomic activity and on specified ecosystems. Each program is required to establish links and partnerships with stakeholders and decision makers so that research results can be translated into usable knowledge and decision-support tools that are specific to the subregion. Emphasis is placed not only on assessing the climate sensitivity of different activities and ecosystems but also on their vulnerabilities to climate variability and change and on policies and programs that would increase the resilience of these subregions to climate-related risks of varying magnitude.

So far RISA teams cover the Pacific Northwest, the Southwest, the Colorado River system, California, Hawaii, the Southeast (Florida and Georgia), the Carolinas, and New England. Although the basic template and objectives for each team are the same, there is considerable variation in the way the teams implement the vision because each team is grounded in a particular place in which the mix of concerns varies along with constituents, capabilities, and climate-related risks. These teams document what and how climate drivers function in specific places, what impacts they typically exert on various kinds of natural systems and socioeconomic activities that are sensitive to climate variability, and what levels of risk each subregion faces, inter alia. The crucial questions, not surprisingly, shift from place to place. So, for instance, "Will winter snowpack and spring streamflow be above or below normal this year?" might be a critical question in the Pacific Northwest, but it will have no meaning in Florida where "Will it freeze?" is definitely one of the critical questions. In the western United States water is the central issue and will be even more so under scenarios of climate change because the entire West consists largely of snowmelt-driven systems. No matter what their foci, all subregions are now faced with the necessity of trying to understand what their vulnerabilities to anthropogenic climate change are, what the magnitudes and rates of change might be, and how best to adapt to and cope with these changes over time.

The RISA teams clearly demonstrate how useful such an approach can be. But to date this is still a small program and a long way from fulfilling the vision of cohesive observations, data management, data access, carefully designed process studies across regions and subregions nested in a framework for developing regional predictive models of the effects of multiple stresses and translating the research outputs in a series of vigorous and continuing connections with stakeholders.

## NEAR-TERM OPPORTUNITIES

Looking overall at the workshop presentations and discussions, a great range of issues and opportunities were explored. As a final step, the steering committee reviewed the information generated and identified seven near-term opportunities for advancing our understanding of multiple stresses and making this understanding useful to decision makers.

***1. A Ground-Based Measurements Network.*** There is a real need for comprehensive ground-based measurements of important ecological indicators such as biodiversity, species composition, ecosystem functioning, ecological aspects of biogeochemical cycles, and other elements. This information over time will allow improved understanding of the ecological implications of climate change, the evolution of infectious diseases, invasive species, and land use change over time and across large spatial scales (NRC, 2003). The National Ecological Observatory Network (NEON) that has been under development is an example of the kind of system that could contribute the types of information needed.

***2. Global Information Systems and Satellite Observations.*** In 2005 members of the Group on Earth Observations (GEO), which includes 60 countries and the European Commission, agreed to a 10-year implementation plan for a Global Earth Observation System of Systems (GEOSS). Anticipated foci and socioeconomic benefits include

- sustainable agriculture and reduced desertification;
- disaster reduction and improved ecosystem management and protection;
- biodiversity conservation;
- improved weather information, forecasting, and warning;
- adaptation to climate variability and change;
- improved water resource management;
- understanding of environmental factors affecting human health and well-being; and
- improved management of energy resources (NRC, 2005b).

GEOSS could be configured to assist with detecting and understanding multiple stresses and extreme events. For example, one of the key components of the

International Earth Observing System (IEOS),[9] the primary contribution by the United States to GEOSS, would be a National Integrated Drought Information System (NIDIS). The goal of NIDIS is to develop an integrated drought information system that would enhance the ability of users to assess on a timely basis the risks and potential impacts associated with drought through the availability of appropriate decision-support tools. Other aspects of NIDIS focus on the development of a comprehensive drought early warning and delivery system, an enhanced research environment that emphasizes impact mitigation and improved predictive capabilities, and a framework for interacting with and educating stakeholders and the public on causes of drought, preparedness strategies, and how drought impacts human and natural systems. NIDIS is considered to be an invaluable resource in helping water managers and policy makers at all levels deal with the increasing impacts of drought and water resources management in a climate change environment.

IEOS/GEOSS could also provide longer-term forecasting, especially for severe weather events, such as Hurricane Katrina, and an all-hazards, all-media alerting system. (In the case of wildfires, hikers, for example, would get immediate messages on their cell phones to evacuate areas.) Furthermore, as improved forecasting will help with the distribution of resources in warm or cold years and in extreme wet or dry seasons, IEOS/GEOSS could be very important to the water and energy sectors.

***3. Synthesis of Data.*** The Heinz Center's[10] State of the Nation's Ecosystems project—done in concert with federal, corporate, and academic partners—is characterizing data gaps and data integration needs by sector (urban, forests, coasts, etc.) in order to produce indicators on the improvement or degradation of U.S. resources. This multiyear effort could include a section on the composite effect of multiple stresses on ecological and urban sectors and identify missing data most needed to characterize the status of trends of ecosystem health.

***4. Nonlinearities and Thresholds.*** There is a rich historical record of responses to extremes of record (droughts, floods, hurricanes). Overlaying those conditions on the socioeconomic and ecological conditions of today—conducting "what if" scenarios to see if today's communities and natural resources could cope with, for example, the drought of the 1930s or a direct hit of hurricane Andrew on Miami—would be extremely valuable. Similarly, scenarios reconstructing extreme events of the past could study if an increase in temperature and a change in water availability would lead to breakpoints or thresholds in the ecological or economic realms (e.g., as observed by Breshears et al., 2005).

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[9] IEOS, a global system of missions made up of EOS (Earth Observing System) satellites together with other Earth observation missions from NOAA (National Oceanic and Atmospheric Administration), Europe, and Japan.

[10] *http://www.heinzctr.org*.

***5. Resilience.*** Within the assessment processes, institutional, technological, and economic options that offer insurance or appear the most robust to a suite of environmental changes could be identified. These could include such measures as changed cropping patterns, water conservation, germplasm preservation, park design, and habitat connectivity, within the context of long-term resiliency to a changing climate. In addition, early warning systems for various environmental indicators (droughts, floods, tropical cyclones, wildfires) could be established in pertinent regions. Finally, development of a compendium of best practices for coping with extreme events and deployment of appropriate preparedness programs would enhance resilience.

***6. Regional Foci.*** Understanding the impacts of climate change in a particular place in concert with the other environmental stressors operating in that region is key to developing wise coping options. The Regional Integrated Sciences and Assessments program and the regional studies begun under the U.S. National Assessment process are models of this nascent type of analysis, and an increase in this kind of activity is greatly needed.

***7. Stakeholder Involvement.*** Connecting stakeholders to an ongoing research effort directly aimed at producing usable knowledge of value to stakeholders requires long-term partnerships, trust that researchers will actually stay the course, thorough familiarity on both sides about what each is doing, considerable effort expended by the research teams to gain knowledge about the decision context and the needs of the different types of stakeholders, and appreciation by the stakeholders of the added value the results of the research can offer to their concerns. All of this takes time and resources. The RISA teams, for example, have used periodic systematic surveys, annual workshops custom-tailored to the specific interests of different combinations of stakeholders (e.g., water resource managers, forest fire managers, fisheries managers, farmers, coastal managers), and the co-production of specific decision-support tools as ways to build in true stakeholder involvement.

Research and experience to date show that overemphasizing climate forecasts per se is counterproductive. Users have a decided preference for deterministic forecasts and lack of understanding of probabilistic forecasts to an extent that only the technically advanced early adopters find probabilistic climate forecasts to be useful. For others a softer approach is more useful and more readily understood. This approach is grounded on the fact that all stakeholders really want to understand to what extent climate is responsible for the underlying variation in the resources they use or manage or the economic activities in which they are engaged. Once researchers recognize this fact, it is possible to have fruitful, long-term relationships that evolve. However, each party to the relationship has to be committed to learning from the other, and the researchers need to strive to produce information and decision tools that are useful and timely to the stakeholders. However, it should be understood that stakeholders cannot define the totality of the research agenda for the simple reason that often the stakeholders do not and cannot be expected to know what they need to know about the dynamics of the climate system. So the research agenda must be balanced; it cannot be the product of curiosity alone but rather it must be defined to meet certain ends that can be transferred to the decision maker.

# References

Allen, C. D., and D. D. Breshears. 1998. Drought-induced shift of a forest-woodland ecotone: Rapid landscape response to climate variation. Proceedings of the National Academy of Sciences U.S.A. 95:14839-14842.

Andreae, M. O., D. Rosenfeld, P. Artaxo, A. A. Costa, G. P. Frank, K. M. Longo, and M. A. F. Silva-Dias. 2004. Smoking rain clouds over the Amazon. Science 303:1337-1342.

Arrhenius, S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. The London, Edinburgh and Dublin Philosophical Magazine and Journal of Sciences 41:237-276.

Bacastow, R., and C. D. Keeling. 1973. Atmospheric carbon dioxide and radiocarbon in the natural carbon cycle. II. Changes from A.D. 1700 to 2070 as deduced from a geochemical reservoir. Pp. 86-135 in G. M. Woodwell and E. V. Pecan, eds. *Carbon and the Biosphere*. Springfield, Virginia: U.S. Department of Commerce.

Botterill, L. 2005. Late twentieth century approaches to living with uncertainty: The national drought policy. In *From Disaster Response to Risk Management: Australia's National Drought Policy,* L. C. Botterill and D. A. Wilhite, eds. Dordrecht, The Netherlands: Springer Publishers.

Breshears, D. D., N. S. Cobb, P. M. Rich, K. P. Pricee, C. D. Allen, R. G. Balice, W. H. Romme, J. H. Kastensf, M. L. Floyd, J. Belnapl, J. J. Anderson, O. B. Myers, and C. W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Sciences U.S.A. 102:15144-15148.

Cayan, D. R., S. A. Kamerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson. 2001. Changes in the onset of spring in the western United States. Bulletin of the American Meteorological Society 82:399-415.

Chapin, F. S., M. Sturm, M. C. Serreze, J. P. McFadden, J. R. Key, A. H. Lloyd, A. D. McGuire, T. S. Rupp, A. H. Lynch, J. P. Schimel, J. Beringer, W. L. Chapman, H. E. Epstein, E. S. Euskirchen, L. D. Hinzman, G. Jia, C. L. Ping, K. D. Tape, C. D. C. Thompson, D. A. Walker, and J. M. Welker. 2005. Role of land-surface changes in Arctic summer warming. Science 310:657-660.

Charney, J., P. H. Stone, and W. J. Quirk. 1975. Drought in the Sahara: A biogeophysical feedback. Science 187:434-435.

Charney, J. G., W. J. Quirk, S-H. Chow, and J. Kornfield. 1977. A comparative study of effects of albedo change on drought in semiarid regions. Journal of the Atmospheric Sciences 34:1366-1385.

Clark, J. S., E. C. Grimm, J. J. Donovan, S. C. Fritz, D. R. Engstrom, and J. E. Almendinger. 2002. Drought cycles and landscape responses to past aridity on prairies of the northern Great Plains, USA. Ecology 83(3):595-601.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle. 2004. Long-term aridity changes in the western United States. Science 306:1015-1018.

Cox, P. M., R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408:184-187.

Dickinson, R. E., and A. Henderson-Sellers. 1988. Modelling tropical deforestation: Study of GCM land-surface parameterizations. Quarterly Journal of the Royal Meteorological Society 114:439-462.

Enfield, D. B., and L. Cid-Serrano. Forthcoming. Projecting the risk of future climate shifts. International Journal of Climate.

Feddema, J. J., K. W. Oleson, G. B. Bonan, L. O. Mearns, L. E. Buja, G. A. Meehl, and W. M. Washington. 2005. The importance of land-cover change in simulating future climates. Science 310:1674-1678.

FEMA (Federal Emergency Management Agency). 1995. *National Mitigation Strategy*. Washington, D.C.: FEMA.

Friedlingstein, P. 2004. Climate carbon cycle interactions. Pp. 217-224 in *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World,* C. B. Field and M. R. Raupach, eds. Washington, D.C.: Island Press.

Fung, I., S. C. Doney, K. Lindsay, and J. John. 2005. Evolution of carbon sinks in a changing climate. Proceedings of the National Academy of Sciences U.S.A. 102:11201-11206.

Gibbard, S., K. Caldeira, G. Bala, T. J. Phillips, and M. Wickett. 2005. Climate effects of global land cover change. Geophysical Research Letters 32:L23705.

Gray, S. T., C. L. Fastie, S. T. Jackson, and J. L. Betancourt. 2004. Tree-ring-based reconstruction of precipitation in the Bighorn Basin, Wyoming, since 1260 A.D. Journal of Climate 17(19):3855-3865.

Hagman, G. 1984. *Prevention Better than Cure: Report on Human and Natural Disasters in the Third World*. Stockholm: Swedish Red Cross.

Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. Journal of Climate 18(21):4545-4561.

Hayes, M. J., M. D. Svoboda, C. L. Knutson, and D. A. Wilhite. 2004a. Estimating the economic impacts of drought. Proceedings of the 14th Conference on Applied Climatology, Seattle, Washington, January 11-15.

Hayes, M. J., O. V. Wilhelmi, and C. L. Knutson. 2004b. Reducing drought risk: Bridging theory and practice. Natural Hazards Review 5:106-113.

Hoerling, M., and A. Kumar. 2003. The perfect ocean for drought. Science 299:691-694.

IPCC (Intergovernmental Panel on Climate Change). 1990. *First Assessment Report*. Cambridge, England: Cambridge University Press.

IPCC. 1995. *Second Assessment Report: Climate Change*. Cambridge, England: Cambridge University Press.

IPCC. 2001. *Third Assessment Report: Climate Change*. Cambridge, England: Cambridge University Press.

ISDR (International Strategy for Disaster Reduction) Ad Hoc Discussion Group on Drought. 2003. *Living with Risk: An Integrated Approach to Reducing Society's Vulnerability to Drought.* Geneva, Switzerland: ISDR.

Jackson, R. B., E. G. Jobbagy, R. Avissar, S. B. Roy, D. J. Barrett, C. W. Cook, K. A. Farley, D. C. le Maitre, B. A. McCarl, and B. C. Murray. 2005. Trading water for carbon with biological carbon sequestration. Science 310:1944-1947.

Karnosky, D. F., B. Mankovska, K. Percy, R. E. Dickson, G. K. Podila, J. Sober, A. Noormets, G. Hendrey, M. D. Coleman, M. Kubiske, K. S. Pregitzer, and J. G. Isebrands. 1999. Effects of tropospheric $O_3$ on trembling aspen and interaction with $CO_2$: Results from an $O_3$-gradient and a FACE experiment. Journal of Water, Air and Soil Pollution 116:311-322.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. Journal of Climate 19(18):4545-4559.

Knutson, C., M. J. Hayes, and T. Phillips. 1998. *How to Reduce Drought Risk*. Lincoln, Nebraska: National Drought Mitigation Center.

Lean, J., and D. A. Warrilow. 1989. Simulation of the regional climatic impact of Amazon deforestation. Nature 342:411-413.

Mack, M. C., E. A. G. Schuur, M. S. Bret-Harte, G. R. Shaver, and F. S. Chapin. 2004. Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization. Nature 431:440-443.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. Proceedings of the National Academy of Sciences U.S.A. 101:4136-4141.

MEA (Millennium Ecosystem Assessment). 2005. *Strengthening Capacity to Manage Ecosystems Sustainability for Human Well-Being*. Washington, D.C.: Island Press.

NAST (National Assessment Synthesis Team). 2000. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*. U.S. Global Change Research Program. Cambridge, England: Cambridge University Press.

Nepstad, D. C., A. Veríssimo, A. Alencar, C. Nobre, E. Lima, P. Lefebvre, P. Schlesinger, C. Potter, P. Moutinho, E. Mendoza, M. Cochrane, and V. Brooks. 1999. Large-scale impoverishment of Amazonian forests by logging and fire. Nature 398:505-508.

NRC (National Research Council). 1999. *Our Common Journey: A Transition Toward Sustainability*. Washington, D.C.: National Academy Press.

NRC. 2002. *Science for the Sustainability Transition*. Washington, D.C.: The National Academies Press.

NRC. 2003. *Communicating Uncertainties in Weather and Climate Information: A Workshop Summary*. Washington, D.C.: The National Academies Press.

NRC. 2004a. *Climate Data Records from Environmental Satellites*. Washington, D.C.: The National Academies Press.

NRC. 2004b. *NEON: Addressing the Nation's Environmental Challenges*. Washington, D.C.: The National Academies Press.

NRC. 2005a. *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*. Washington, D.C.: The National Academies Press.

NRC. 2005b. *Improving the Scientific Foundation for Atmosphere-Land-Ocean Simulations: Report of a Workshop*. Washington, D.C.: The National Academies Press.

O'Meagher, B., M. Stafford Smith, and D. H. White. 2000. Approaches to integrated drought risk management. Pp. 115-128 in *Drought: A Global Assessment* (Volume 2), D. A. Wilhite, ed. London, U.K.: Routledge Publishers.

Pacala, S. W., G. C. Hurtt, D. Baker, P. Peylin, R. A. Houghton, R. A. Birdsey, L. Heath, E. T. Sundquist, R. F. Stallard, P. Ciais, P. Moorcroft, J. P. Caspersen, E. Shevliakova, B. Moore, G. Kohlmaier, E. Holland, M. Gloor, M. E. Harmon, S. M. Fan, J. L. Sarmiento, C. L. Goodale, D. Schimel, and C. B. Field. 2001. Consistent land- and atmosphere-based U.S. carbon sink estimates. Science 292:2316-2319.

Prentice, I. C., G. D. Farquhar, M. J. R. Fasham, M. L. Goulden, M. Heimann, V. J. Jaramillo, H. S. Kheshgi, C. Le Quéré, R. J. Scholes, and D. W. R. Wallace. 2001. The carbon cycle and atmospheric carbon dioxide. Pp. 183-237 in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, eds. Cambridge, United Kingdom, and New York, NY, USA: Cambridge University Press.

Rial, J. A., R. A. Pielke Sr., M. Beniston, M. Claussen, J. Canadell, P. Cox, H. Held, N. de Noblet-Ducoudre, R. Princc, J. F. Reynolds, and J. D. Salas. 2004. Nonlinearities, feedbacks and critical thresholds within the earth's climate system. Climatic Change 65:11-38.

Sabine, C. L., M. Heiman, P. Artaxo, D. C. E. Bakker, C-T. A. Chen, C. B. Field, N. Gruber, C. LeQuéré, R. G. Prinn, J. E. Richey, P. Romero-Lankao, J. A. Sathaye, and R. Valentini. 2004. Current status and past trends of the carbon cycle. Pp. 17-44 in *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*. C. B. Field and M. R. Raupach, eds. Washington, D.C.: Island Press.

Salati, E., and P. B. Vose. 1984. Amazon Basin: A system in equilibrium. Science 225:129.

Shaver, G. R., A. E. Giblin, K. J. Nadelhoffer, K. K. Thieler, M. R. Downs, J. A. Laundre, and E. B. Rastetter. 2006. Carbon turnover in Alaskan tundra soils: Effects of organic matter quality, temperature, moisture and fertilizer. Journal of Ecology 94:740-753.

Shukla, J., C. Nobre, and P. Sellers. 1990. Amazon deforestation and climate change. Science 247:1322-1325.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate 18:1136-1155.

Strauss, D., L. Bednar, and R. Mees. 1989. Do one percent of forest fires cause ninety-nine percent of the damage? Forest Science 35:319-328.

Vitousek, P. M., J. Aber, R. W. Howarth, G. E. Likens, P. A. Matson, D. W. Schindler, W. H. Slesinger, and G. D. Tilman. 1997. Human alteration of the global nitrogen cycle: Causes and consequences. Issues in Ecology, No. 1, Spring.

Western Governors' Association. 2004. *Creating a Drought Early Warning System for the 21st Century: The National Integrated Drought Information System*. Denver, Colorado.

Wilhite, D. A. 1991. Drought planning: A process for state government. Water Resources Bulletin 27(1):29-38.

Wilhite, D. A., and M. Buchanan-Smith. 2005. Drought as hazard: Understanding the natural and social context. Pp. 3-32 in *Drought and Water Crises: Science, Technology, and Management Issues,* D. A. Wilhite, ed. Boca Raton, Florida: CRC Press.

WMO/UNEP (World Meteorological Organization/United Nations Environment Programme). 1985. *Atmospheric Ozone: Assessment of Our Understanding of the Processes Controlling its Present Distribution and Change: 1985*. Report No. 16, 3 volumes. Geneva, Switzerland: WMO.

WMO. 1989. *Scientific Assessment of Stratospheric Ozone: 1989*. Global Ozone Research and Monitoring Project Report No. 20. Geneva, Switzerland: WMO.

WMO. 1991. *Scientific Assessment of Ozone Depletion: 1991*. Global Ozone Research and Monitoring Project, Report No. 25. Geneva, Switzerland: WMO.

WMO. 1994. *Scientific Assessment of Ozone Depletion: 1994*. Geneva, Switzerland.

WMO. 1998. *Scientific Assessment of Ozone Depletion: 1998*. Geneva, Switzerland.

WMO. 2002. *Scientific Assessment of Ozone Depletion: 2002*. Geneva, Switzerland.

Woodhouse, C. A., and J. T. Overpeck. 1998. 2000 years of drought variability in the central United States. Bulletin of the American Meteorological Society 79:2693-2714.

Woodwell, G. M., J. E. Hobbie, R. A. Houghton, J. M. Melillo, and B. Moore. 1983. Global deforestation: Contribution to atmospheric carbon dioxide. Science 222:1081-1086.

# APPENDIX A

# Statement of Task

This workshop will use key presentations, case examples, panelist discussion, and open discussion to explore current understanding of multiple environmental stresses in the earth-atmosphere system on natural, managed, and socioeconomic systems, and discuss the types of research needed to improve integrated understanding of these kinds of complex, nonlinear problems.

Workshop presenters and participants are asked to discuss the following questions:

- For the case examples and in general, what is the state of the knowledge base related to the coupling between physical, chemical, ecological, and human systems? What research has been done or is being done in the area of multiple stresses?
- For the case examples and in general, how do multiple stresses interact on different temporal and spatial scales? What does this imply for management options?
- For the case examples and in general, what are the potential nonlinearities in response to multiple stresses?
- How can we improve our capability of integrating scientific knowledge so that we are better able to deal with complex multiple stresses, including uncertainty, in decision-support systems?
- What research, conducted at the regional or sectoral level, might best promote analysis of multiple stresses and provide information useful to decision makers?

# APPENDIX B

# Workshop Agenda

### Understanding and Responding to Multiple Environmental Stresses: A Workshop
### September 29-30, 2005

The Arnold and Mabel Beckman Center
100 Academy
Irvine, California

### THURSDAY, SEPTEMBER 29

8:30 A.M. **Welcome and Introductions**
Mary Anne Carroll, University of Michigan, and Rosina Bierbaum, University of Michigan (Steering Committee Co-chairs)

**Workshop Objectives**
Chris Elfring (Director, BASC)

9:00 A.M. **Keynote Address: What Do We Mean by "Multiple Environmental Stresses" and Why Do We Care?**
Eric Barron, Pennsylvania State University

9:45 A.M. **Introduction to Case Study I: Drought as an Example of a Multiple Stress Scenario**
Donald Wilhite, University of Nebraska (Steering Committee)

10:30 A.M. Break

11:00 A.M. **Understanding Hazard and Predictability of Drought**
Facilitator: Donald Wilhite, University of Nebraska (Steering Committee)

- Jonathan Overpeck, University of Arizona
- Kelly Redmond, Western Regional Climate Center, Desert Research Institute
- Phil Pasteris, National Water and Climate Center, U.S. Department of Agriculture
- Discussion and Questions

12:30 P.M. Lunch

1:30 P.M. **Understanding Vulnerability and Response Strategies to Drought**
Facilitator: Jonathan Overpeck, University of Arizona

- William Easterling, Pennsylvania State University
- David Breshears, University of Arizona
- Roger Pulwarty, NOAA/CIRES/Climate Diagnostics Center
- Donald Wilhite, University of Nebraska (Steering Committee)
- Discussion and Questions

3:30 P.M. Break

4:00 P.M. **Case Study I Wrap-up: Research Needs to Understand and Respond to the Multiple Environmental Stresses that Lead to Drought**
Facilitator: Edward Miles, University of Washington (Steering Committee)

5:30 P.M. Adjourn

6:30 P.M. Dinner

7:30 P.M. **Dinner Speaker: The Millennium Ecosystem Assessment (MEA) and How It Helps Us Understand the Impacts of Multiple Stresses**
Harold Mooney, Stanford University

8:30 P.M. Adjourn

## FRIDAY, SEPTEMBER 30

8:00 A.M. **Introduction to Case Study II: Atmosphere-Ecosystem Interactions and Lessons About Multiple Stresses**
Jerry Melillo, Marine Biological Laboratory

8:45 A.M. **Understanding Atmosphere-Biosphere Interactions**
Facilitator: Mary Anne Carroll, University of Michigan (Steering Committee)
- Ronald Prinn, Massachusetts Institute of Technology
- Scott Doney, Woods Hole Oceanographic Institution
- Alex Guenther, National Center for Atmospheric Research
- John Reilly, Massachusetts Institute of Technology
- Jerry Melillo, Marine Biological Laboratory
- Discussion and Questions

10:30 A.M. Break

10:45 A.M. **Understanding Vulnerability of Ecosystem Goods and Services and Response Strategies**
Facilitator: Rosina Bierbaum, University of Michigan (Steering Committee)
- William Easterling, Pennsylvania State University
- David Breshears, University of Arizona
- Patricia Romero Lankao, Autonomous Metropolitan University, Xochimilco, Mexico
- Richard Norgaard, University of California, Berkeley
- Discussion and Questions

12:30 P.M. Lunch

1:30 P.M. **Case Study II Wrap-up: Research Needs to Understand and Respond to Multiple Environmental Stresses in Atmosphere-Ecosystem Interactions**
Facilitator: Christopher Field, Carnegie Institution (Steering Committee)

2:30 P.M. **Synthesis of Workshop Findings: Multiple Environmental Stresses—Knowledge Gaps and Future Directions**
Facilitators: Mary Anne Carroll, University of Michigan, and Rosina Bierbaum, University of Michigan (Steering Committee Co-chairs)

4:30 P.M. Adjourn

# APPENDIX C

# Workshop Participants

Eric Barron, *Pennsylvania State University*
David Breshears, *University of Arizona*
Antonio Busalacchi, *University of Maryland, College Park*
Scott Doney, *Woods Hole Oceanographic Institution*
William Easterling, *Pennsylvania State University*
Jay Famiglietti, *University of California, Irvine*
Kristie Franz, *University of California, Irvine*
Alex Guenther, *National Center for Atmospheric Research*
Diana Josephson, *National Center for Atmospheric Research*
Chester Koblinsky, *NOAA*
Jane Leggett, *EPA*
Jerry Melillo, *Marine Biological Laboratory*
Harold Mooney, *Stanford University*
Richard Norgaard, *University of California, Berkeley*
Jonathan Overpeck, *University of Arizona*
Gi-Hyeon Park, *University of California, Irvine*
Phil Pasteris, *USDA/National Water and Climate Service*
Ronald Prinn, *Massachusetts Institute of Technology*
Roger Pulwarty, *NOAA/CIRES*
Kelly Redmond, *Desert Research Institute*
John Reilly, *Massachusetts Institute of Technology*
Patricia Romero Lankao, *Autonomous Metropolitan University, Xochimilco, Mexico*
Richard Rosen, *NOAA*

Dongryeol Ryu, *University of California, Irvine*
Thomas Vonder Haar, *Colorado State University*

## Committee

Rosina Bierbaum, *University of Michigan*
Mary Anne Carroll, *University of Michigan*
Christopher Field, *Carnegie Institution of Washington*
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# APPENDIX D

# Extended Speaker Abstracts[1]

## ADDRESSING MULTIPLE STRESSES

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The nature of the environmental issues facing any nation demands a capability that allows us to enhance economic vitality, maintain environmental quality, limit threats to life and property, and strengthen fundamental understanding of the earth. In each case it is the ability to anticipate the future (e.g., a forecast of an impending storm, a prediction of the water quality change in response to a new source of pollutant) that makes information about the earth system truly useful. Reliable information about the future (i.e., predictions) is the key to addressing environmental issues. However, society requires greater access to and greater confidence in both information and forecasts or projections in order to weigh the advantages and risks of alternative courses of action by private and public decision makers. Such information is a key commodity in enhancing economic vitality and societal well-being. What stands in our way of providing this information?

### THE NATURE OF THE PROBLEM

The driving forces that alter environmental quality and integrity are widely recognized, involving primarily weather and climate, patterns of land use and

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[1] Presented in the order given during the workshop.

land cover, and resource use with its associated waste products. But a key feature of most regions is that more than one driving force is changing simultaneously. Consequently, most locations are characterized by multiple stresses. The effect of a combination of environmental stresses is seldom simply additive. Rather, they often produce amplified or damped responses, unexpected responses, or threshold responses in environmental systems. Multiple, cumulative, and interactive stresses are clearly the most difficult to understand and hence the most difficult to manage.

In contrast, most research, analysis, and policy are based on studies that examine discrete parts of these complex problems. Basically, earth and environmental sciences tend to focus on cause and effect, where we seek to understand how a specific element of the system may respond to a specific change or perturbation (e.g., acid rain on lake fisheries). The lack of an ability to assess the response of the system to multiple stresses limits our ability to assess the impacts of specific human perturbations, to assess advantages and risks, and to enhance economic and societal well-being in the context of global, national, and regional stewardship.

However, the problem is not limited simply to moving from analysis of discrete parts of complex problems to a more comprehensive analysis.

First, economic vitality and societal well-being are increasingly dependent on combining global, regional, and local perspectives. A “place-based” imperative for environmental research stems from the importance of human activities on local and regional scales, the importance of multiple stresses on specific environments, and the nature of the spatial and temporal linkages between physical, biological, chemical, and human systems. We find the strongest intersection between human activity, environmental stresses, earth system interactions and human decision making in regional analysis coupled to larger spatial scales.

Second, a decade of research on greenhouse gas emissions, ozone depletion, and deforestation has clarified many critical unanswered questions. However, the last decade of effort has also revealed a number of challenges, most notably the challenge of creating integrated global observational capabilities and the computational and scientific limitations inherent in creating a truly integrated, global, coupled system modeling capability suitable for assessing impacts and adaptations. These problems are noteworthy in global change science, but they become intractable at the scales of human decision making. A major part of the problem is simply a matter of scale combined with the sheer information required to combine physical, biological, chemical, and human systems if the framework is global. For example, whereas a global integrated observing system is challenging but tractable and plays a fundamental role on the scale of a global circulation model, it collapses under its own weight at higher spatial resolutions if we demand a truly comprehensive data system involving the host of observations spanning biology, hydrology, soils, weather, etc., required to address problems at the scales of human decision making. For this reason, we have never fully realized the objective of "earth system science."

Recognition of the importance of developing a more integrated approach to environmental research was abundantly clear in the *U.S. National Assessment of Climate Change Impacts on the United States* (NAST, 2000). The first recommendation for future research focused on developing a more integrated approach to examining impacts and vulnerabilities to multiple stresses. There were many examples in which the key limitation to the assessment of potential impacts to climate change was a lack of knowledge of other stressors. For example, changes in insect-, tick-, and rodent-borne diseases could be clearly tied to weather and climate, but a number of other environmental factors that could influence the disease vectors (e.g., the importance of land cover/land use on disease hosts), transmission dynamics, and population vulnerabilities severely limited our ability to make robust conclusions on how climate change might influence the distribution and occurrence of many infectious diseases in the future.

## ADDRESSING SOCIETAL NEEDS

The need for society to enhance economic vitality, while maintaining environmental quality and limiting threats to property and life, should drive the environmental research and operational enterprise. These societal needs lead to a vision that requires a focus on multiple stresses. To address this vision, we need to develop a comprehensive regional framework for environmental science. This vision includes five elements:

1. an integrated regional web of sensors, including physical, chemical, biological, and socioeconomic factors, that link existing observations into a coherent framework and enable new observations to be developed within an overall structure;
2. an integrated and comprehensive regional information system, accessible to a wide variety of researchers, operational systems, and stakeholders;
3. directed process studies designed to examine specific phenomena through field study to address deficiencies in understanding;
4. a regional, high-resolution modeling foundation for constructing increasingly complex coupled system models at the spatial and temporal scales appropriate for the examination of specific and integrated biological, hydrological, and socioeconomic systems; and
5. a strong connection to significant regional issues and stakeholders.

These five elements are described in detail below:

***1. A Web of Integrated Sensors***. The current U.S. observation strategy appears to be haphazard when viewed in the overall context of environmental problems. The reason is clear. The observations are driven by different mission needs and tend to focus on the measurement of discrete variables at a specific set of locations designed to serve the different needs of weather forecasting, pollution monitoring, hydrological forecasting, or other objectives. The mission focus results in a diverse set of networks that are supported by a large number of different federal agencies, states, or regional governments. Increased awareness of a host of environmental issues drives demand for additional new observations. However, these new observations are frequently viewed independently of any overall structure or integrated observing strategy. Operational needs and research or long-term monitoring needs are also often independent. Importantly, regular and consistently repeated observations present added challenges in garnering sufficient financial resources. The end result is almost certainly fiscally inefficient, and undoubtedly limits our ability to integrate physical, biological, chemical, and human systems.

The limitations of the current observing strategy are widely recognized, and they have spurred efforts to develop global observing systems for global change, climate, and oceanic and terrestrial systems in the international arena. These efforts are commendable and must be encouraged, but they are also extremely challenging because of the breadth of measurements, nations, capabilities, and policies that are involved.

In contrast, at a regional level in the United States we have the potential to (a) link observing systems into a web of integrated sensors building upon existing weather and hydrological stations and remote sensing capability; (b) create the agreements across a set of more limited agencies and federal, state, and local governments needed to create a structure to the observing system; (c) provide a compelling framework that encourages or demands the integration of new observations into a broader strategy; and (d) create strong linkages between research and operational observations that result in mutual benefit. The result is likely to create new efficiencies through the development of measurement systems that are more comprehensive, rather than a suite of separately funded, disconnected systems. The result is also likely to result in greater scientific benefit to society and greater understanding due to the co-location or networking of many different measurement capabilities. The demonstration of fiscal efficiency and improved capability and resulting benefit are likely to create a significant additional impetus for developing national and global integrated observing systems.

***2. Regional Information Systems***. Society has amassed an enormous amount of data about the earth. New satellite systems and other observational capabilities promise enormous increases in the availability of earth data. Fortunately, technological innovations are allowing us to capture, process, and display this information in a manner that is multiresolution and four-dimensional. The major challenges involve data management; the storage, indexing, referencing, and retrieving of data; and the ability to combine, dissect, and query information. The ability to navigate this information, seeking data that satisfy the direct needs of a variety of users, is likely to spark a new "age of information" that will promote economic benefit and engender new research directions and capabilities to integrate physical, biological, chemical, and human systems.

The efforts to create comprehensive information systems increasingly reflect federal and state mandates to make data more accessible and useful to the public and to ensure that our investments in research yield maximum societal benefit. The development of a global digital database is again an enormous challenge. In contrast, a regional or state focus becomes a logical test bed, enabling the participation of universities; federal, state, and local governments; and industry in the development of a regional information system that is tractable and for which immediate benefit for a state or region can be evident. Again, the demonstration of capability and resulting benefit are likely to create a significant additional impetus for developing national and global information systems.

***3. Framework for Process Studies***. Process studies are a critical element of scientific advancement because they are designed, through focused observations and modeling, to probe uncertainties in knowledge about how the earth system functions. In many cases mismatch between model predictions and observations can drive targeted investigations to limit the level of error. Frequently, efforts to couple different aspects of the earth system (e.g., the atmosphere and land-surface vegetation characteristics) prompt targeted exploration because the level of understanding is still rudimentary. The objective is to use field study to address deficiencies in our understanding. The benefit of these intensive studies is maximized when they can be coupled with a highly developed, integrated set of sensors, with readily accessible spatial and temporal data within a regional information system, and with a predictive model framework that readily enables the entrainment and testing of new information from process studies. Hence, a regional focus is empowered by process studies that are directly tied to answering specific questions designed to assess the impacts of specific human perturbations, to assess advantages and risks, and to enhance economic and societal well-being.

***4. Predictive Capability***. The value of reliable advanced information is widely recognized. For example, we have considerable experience with the benefit of reliable weather forecasts, whether it involves the planning of a day around a precipitation forecast, the protection of life and property that stems from severe weather warnings, or the economic benefit of weekly, seasonal, or interannual forecasts used by climate- or weather-sensitive industries such as agriculture, forestry, fisheries, construction, or transportation. For example, millions of dollars in commodity markets can be saved by regional utilities with advanced weather or seasonal forecasts, and El Niño forecasts a season in advance can substantially modify agricultural practice.

Prediction is central to the translation of knowledge about the earth system into economic benefit and societal well-being. Over the last several decades we have experienced enormous increases in our ability to forecast weather and to project climate and climate variability into the future. The demand for new forecasting products, involving air quality, energy demand, water quality and quantity, ultraviolet radiation, and human health indexes is also growing rapidly, and as we demonstrate feasibility and benefit, society is likely to demand a growing number of new operational forecast products on prediction timescales of days to decades into the future. Further, we already clearly sense that environmental issues will demand an even greater capability to integrate physical, biological, chemical, and human systems in order to develop the predictive capability needed to examine the response of critical regions or cases to multiple stresses.

Global weather and climate models provide the strongest physical foundation for more comprehensive predictive capability. The numerical models that underpin this type of forecast are increasingly becoming the framework for the addition of new numerical formulations designed to predict air quality, the water balance for river forecast models, and a host of other variables, including the migration of forests under climate change conditions. As we attempt to produce predictions at the scale of human endeavors, mesoscale models (capable of predicting synoptic weather systems) and downscaling of coarser resolution model output are increasingly becoming the focal point of weather and climate studies because of their potential to make predictions on the scale of river systems, cities, agriculture, and forestry. Enormous potential exists if we can institutionalize a mesoscale numerical prediction capability that meshes with regional sensor webs and information systems. Such a capability enables a strategy and implementation capability for building tractable coupled models, initiating experimental forecasts of new variables, assessing the outcomes associated with multiple stresses, and taking advantage of the discipline of the forecasting process to create a powerful regional prediction capability. This capability, built upon the numerical framework of weather and climate models, can be extended to air quality, water quantity and quality, ecosystem health, human health, agriculture, and a host of other areas.

It is time to bring a demanding level of discipline to the forecasting of a wide variety of environmental variables. The objective is to stimulate the interplay between improvements in observation, theory, and practice needed to develop capabilities of broad value to society. The discipline of forecasting is dependent on four steps: (1) collection and analysis of observations of present conditions; (2) use of subjective or quantitative methods to infer future conditions; (3) assessment of the accuracy of the prediction with observations; and (4) analysis of the results to determine how methods and models can be improved. At a minimum we are capable of bringing a much greater level of structure and discipline into our predictions of the future, ranging from specific forecasts to statistical ensembles that include a measure of expected accuracy to an assessment of the range of possibilities.

***5. Creation of a Vigorous and Continuous Link to Users and Decision Makers***. We need to create a vigorous connection between the research and decision makers by (a) incorporating the variety of space and timescales and the diversity of variables that are important to decision makers; (b) emphasizing the education of the user in the meaning and significance of climate and land use information in order to promote greater use and more robust applications; (c) ensuring mutual information exchange and feedback; (d) focusing on communication and accessibility of information; (e) continuously evaluating and assessing the use and effectiveness of the services; (f) employing active mechanisms to enable the transition from research discovery to useful products; and (g) employing a variety of methods of education and outreach.

## SUMMARY

The above structure is inherently a hybrid between research and operational functions. Both benefit from the level of integration of observations and information, the targeted process studies, and the model development capability. An emphasis on a region-specific predictive capability will drive the development of new understanding and new suites of comprehensive interactive high-resolution models that focus on addressing societal needs. A key objective is to bring a demanding level of discipline to "forecasting" in a broad arena of environmental issues. Common objectives and an integrated framework will also engender new modes and avenues of research and catalyze the development of useful operational products. With demonstrated success, the concepts of integrated regional observation and information networks, combined with comprehensive models, will grow into a national capability that far exceeds current capabilities. Such a capability is designed to address a broad range of current and future regional and global environmental issues.

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# DROUGHT: OBSERVATIONS, MECHANISMS, POTENTIAL SURPRISES AND CHALLENGES

*Jonathan Overpeck*
*University of Arizona*

## INTRODUCTION

Drought is one of the most challenging and costly environmental concerns confronting society. Over time, many institutions have been developed to deal with drought, but there is still a regular multi-billion dollar annual drought impact in the United States alone. Moreover, a complete consideration of drought provides a sobering view of the future. The purpose of this presentation is to provide an overview of drought variability and related issues.

Drought is a concern worldwide, but by necessity this presentation will focus on North America only. Nonetheless, many of the North American lessons can inform climate-society debates elsewhere—particularly in Africa, where there is also a rich history of observations, as well as research on the causes and impacts of drought variability.

## THE INSTRUMENTAL RECORD OF DROUGHT

Drought is always affecting some part of North America, and even a single-year drought has impact and is thus important. The longer droughts are of greater concern, with the droughts of the 1930s, 1950s, and 1999 to the present being the droughts of record and of most concern. These longer droughts all affected large portions of North America. The most recent drought is particularly notable in that it was hotter than the similar drought of the 1950s. In general, western North America has seen significant warming over the last 100 years, particularly in the last couple of decades.

It is notable that the recent period of unprecedented population increase in the western United States coincided with one of the wettest periods on record. It is also troubling that Colorado River water was divided up among basin states during the one of the other wettest periods: in total, 16.5 MAF of water was allocated per year, even though the measured flow during the early 20th century wet period was less than 15 MAF per year.

## THE PALEOCLIMATIC RECORD OF DROUGHT

Even a quick glance at the paleoclimate record of drought makes it clear that the instrumental record provides a biased record of drought due to a shortness of record. Droughts comparable to the 1930s, 1950s or early 2000s have occurred, in general, once or twice per century over the last 2,000 years. The true long-term average flow of the Colorado is well below what is allocated to western states and Mexico. All droughts of the 20th century were eclipsed by past droughts, both in terms of annual maximum severity, duration, and geographic extent. It is clear from the paleoclimatic record that droughts longer than a decade (i.e., "megadroughts") were not that rare and that droughts impacting much of the western United States have lasted as long as a century or more within the last 2,000 years. Paleoclimatic research has shown that at least one lake in the Sierra Nevada of western North America went dry for decades on more than one occasion—something that has not occurred since Europeans settled the West. The true range of "natural" drought variability is thus substantially larger and more complex than suggested by the last century of instrumental drought variation.

In general, most of the large droughts of the western United States have been large enough to affect more than one major river basin at a time, and some (e.g., the late 16th-century megadrought) apparently impacted the United States from coast to coast and from northern to southern borders. Many (all?) long-duration droughts moved spatially from year to year and usually included years with normal or above-normal rainfall.

Another key aspect of drought variability illuminated by the paleoclimatic record is that decades- to centuries-long hydrological "regimes" (e.g., characterized by rare/short or frequent/longer droughts) have begun and ended abruptly—transitions between drought regimes can take place over years to decades, whereas the regimes themselves can be significantly longer.

## MECHANISMS OF DROUGHT VARIABILITY

Great strides have been made recently with respect to understanding the proximal cause of drought in North America. We have long known that drought in the southwestern United States (e.g., 1950s and the recent drought) have connections with ENSO and that dry winters are favored in La Niña years. More recently, modeling studies have confirmed that anomalous sea surface temperature (SST) patterns, particularly in the tropics, and particularly in the Indo-Pacific, can explain both 20th-century and earlier droughts. Moreover, research has now also identified strong relationships between decadal modes of Pacific and Atlantic variability with decadal patterns of wet and dry conditions over North America. Of course, the major challenge is to explain the causes of the anomalous—and persistent—ocean conditions that lead to North American drought.

Although land-surface feedbacks can play key roles in amplifying or damping drought, it appears that these feedbacks are not dominant in driving temporal drought variability. More work is needed on the role these feedbacks play, but only after recognizing that coupled atmosphere-ocean variability is likely more important.

## POTENTIAL SURPRISES

It is just a matter of time until North America gets hit with a decadal megadrought. This is likely regardless of how large any anthropogenic impact might be. Thus warned, why would anyone be surprised? This shortcoming of human nature needs to be understood and overcome.

## ANTHROPOGENIC VERSUS NATURAL DROUGHT INFLUENCES

The IPCC (TAR and a recent CLIVAR-PAGES-IPCC workshop convened by Overpeck and Trenberth) concluded that anthropogenic forcing will likely increase the probability of drought in central and western North America. Exacerbating this likelihood is the fact that temperatures are already rising significantly in the West, and snowpack is already retreating in the same region (as a result of the warming). A lesson of the paleoclimatic record is that anthropogenic forcing could trigger an abrupt transition into a more drought-prone climatic regime, thus increasing the frequency and duration of drought. Given that these possibilities could materialize with or without significant future human-induced climate change, it makes sense to consider no-regrets strategies to reduce vulnerability to drought in either case.

Most recently it has been proposed that unprecedented warming in the tropical Indian and western Pacific Oceans—likely a result of global warming—is the cause of the ongoing western North American drought. This hypothesis is well supported by modeling studies and is troubling in that the anomalous warming could become the norm in the future in years without El Niño events. If dry conditions intensify this winter, it could be a sign that we are in what could turn out to be the first megadrought since Europeans settled North America.

## CHALLENGES AND OPPORTUNITIES

Needless to say, there is a great deal of additional insight that could be revealed through a more comprehensive study of past drought and megadrought. Can we define the full range of possible drought sufficiently for successful no-regrets adaptation? What are the empirical links between drought and variability in sea surface temperatures? What sets up the anomalous SSTs? Are the anomalies forced or generated by internal variability in the coupled system? What are the potential triggers of abrupt hydrological change? Are there early warning signs to be monitored for? Can droughts and megadroughts be predicted? Are surprises avoidable?

Although the mechanisms of drought cannot be understood fully without much improved observations (particularly paleo), the most important challenge might be in the area of ocean and coupled atmosphere-ocean modeling. Whereas the instrumental record of drought can be simulated fairly well given specified (observed) SST fields, the same drought record cannot be simulated with state-of-the-art coupled models. Clearly, the development of more realistic coupled models must be an urgent priority.

Dealing with drought requires the ability to understand regional climate variability over all seasons and to eventually be able to deliver reliable seasonal to interannual climate outlooks. At present, advances are limited by modeling regional-scale processes, and this limitation is in turn related by the lack of good regional-scale climate monitoring. Thus, there is an increased need for denser in situ climate observing in the topographically complex western epicenter for U.S. drought.

## BOTTOM LINE?

Even if we develop an ability to predict drought, we must work with stakeholders in society (particularly in central and western North America) to develop adaptation strategies that reduce vulnerability to megadrought. There is little doubt that such a drought will occur at some time in the future and that anthropogenic climate change will exacerbate the situation. There is also little doubt that stakeholders and institutions are ill prepared for the inevitable megadrought.

***Jonathan Overpeck*** *is both a professor and director of the Institute for the Study of Planet Earth at the University of Arizona. Dr. Overpeck's research focuses on global and regional climate dynamics. His research aims to reconstruct and understand the full range of climate system variability, recognize and anticipate possible "surprise" behavior in the climate system, understand how the earth system responds to changes in climate forcing, and detect and attribute environmental change to various natural (e.g., volcanic, solar) and nonnatural (e.g., greenhouse gases or tropospheric aerosol) forcing mechanisms. His work also focuses on improving the use of climate knowledge by decision makers in society.*

# UNDERSTANDING HAZARD AND PREDICTABILITY OF DROUGHT

*Kelly T. Redmond*
*Desert Research Institute*

*What are the regional differences in complexities of drought monitoring? What drought monitoring and data needs have been identified for the United States?*

At first blush, drought seems like a simple concept. However, the many ways in which it is expressed show how complex a phenomenon it really can be. The following personal observations elaborate on this point.

## THE DEFINITION OF DROUGHT

Over the years I have attended a large number of drought status meetings, and even if the subject is not discussed right away, sooner or later the conversation turns to a definition of drought. Many definitions are geared toward a specific economic sector, geographic province, or other situation. The definitions of drought attached to these situations are seldom general or readily generalizable, thus rather arbitrary, and thus not very satisfactory. There is a strong predilection to view drought almost solely in terms of its climatic and physical drivers. Most definitions refer to extended periods and to deficient precipitation. But what are the durations and amounts, and perhaps other attributes, that these are referenced to? And is there a single such referent?

It seems unavoidable that the context of the situation where the question is being posed has to be brought into play. And if context matters, then we are led to questions of "deficient from which standpoint?" Water deficiencies can occur when water income is not great enough, or when water outgo is too great. Some drought indices address a mismatch between supply and demand of water (e.g., the Palmer index family), typically in the soil, but a large number do not. Other measures, like the Standardized Precipitation Index (SPI), focus on supply, with the implication that this dominates. Technically, the SPI is not a drought index itself but rather one of many tools to evaluate drought. More generally, though, it seems that drought has come into existence when the amount of water available is not keeping up with expectations or needs. These expectations, in turn, are based on long-term expectations of supply balanced against long-term expectations of demand. What constitutes "long-term" has to do with the timescales for getting into or out of difficulty. These can of course vary quite widely, from hours to centuries, though we generally mean days to months or years, depending on the issue or sector.

A definition is not of much use if it is not always applicable. Nearly every concept of drought involves a water budget (water supply versus water demand) that has somehow come to be "out of balance" over some extended time. For these reasons, I have been led toward a simpler and more widely applicable definition of drought:

*insufficient water to meet needs.*

The main point here is that both supplies and needs (demand) change, so that for a given rate of supply, if demand goes up, the likelihood of shortages arising from typical fluctuations in supply goes up. When Albuquerque's population consisted of 19 people, the deficiency in supply that led to shortages was different from the deficiency in supply that resulted in shortages when there are 600,000 people. Both supply and demand are dynamic.

Furthermore, there are many demands for water from natural systems (vegetation and wildlife and fish), and any useful comprehensive definition of drought has to encompass all biological systems. We could add a clause that refers to the needs of such biological systems, but a simple definition is much more preferable from the standpoint of elegance and clarity of thought.

Even if supply is reduced, if there is still sufficient water to meet all needs, then there is no drought. If supply remains constant, and demand is increased, there can be drought where there was none before. Such imbalances in supply and demand express themselves as impacts. In essence, if there is no impact, there is no drought. Thus, an inescapable corollary that accompanies this line of reasoning is that

*drought is defined by its impacts.*

In routine assessment of drought, such as for the U.S. Drought Monitor, this is the approach commonly taken. This kind of definition is harder to deal with for those who like concrete, definite numbers, because it is "soft" and situation dependent. But I am unable to come up with *any* example of drought that is *not* situation dependent.

Expressing this somewhat differently, an adequate definition or framework for conceptualizing drought ought to work equally well in Death Valley and the Olympic Mountains, in Greenland or Kentucky or Panama or Kihei or Aconcagua. Biological systems in all those places must address water supply and demand.

## REGIONAL DIFFERENCES IN THE CHARACTER OF DROUGHT

It is exactly the regional differences in how we view and describe drought that led to the foregoing train of thought. The nature of the lags in the physical system is of fundamental importance. These lags can be natural or human caused. When there are such lags (from storage mechanisms that depend on water phase—liquid or frozen—or from different types of buffering mechanisms—deep aquifers, reservoirs, porous rock, etc.), generally a system of physical infrastructure, conventions, legal mechanisms, cultural and social practices, and the like will have grown up around them.

In the United States the most striking difference is of course the difference between snowmelt-driven systems and rain-driven systems. These are strongly tied to the seasonal variations in the timing of precipitation, and to temperature, since this influences the phase of new precipitation (liquid or frozen) and the melt and runoff characteristics. Temperature is very important for all of these processes and also affects the demand through the phenological stage. Though not often treated as such, temperature is a hydrological element. All of these factors are elevation dependent and can thus vary over quite small scales (less than a kilometer)—amount, seasonality, phase, vegetative demand, sublimation, and others. To cope with these factors, an elaborate system for tracking and managing water in the West has arisen, in part codified into law, and a large number of dams or other storage mechanisms have also arisen to retain water until it is needed. Furthermore, water flows downhill, so gravitational considerations are a necessity (storage upstream always has more flexibility). Also, somewhat separately, because of the mining heritage, a system of water rights has arisen in the West that is different from that in the East. These factors fold together in intricate and complicated (i.e., nonlinear) ways, with thus the potential for many kinds of interesting behavior.

Another regional factor is the distance between the supply of water and the demand for that same water, often hundreds of miles away, and many months, even years, afterward. The water that supplies desert cities typically arises in locations not even visible from those cities. This water crosses a variety of legal and political boundaries, necessitating a variety of agreements, compacts, and understandings. There are great differences regionally between rain-dominated and more humid environments such as in the eastern United States and the snow-dominated and very arid environments found in the western United States.

In addition there are significant differences among states and across international boundaries in how groundwater is addressed, particularly whether it is considered (legally) to be linked with surface water, even though it is very well known that physically this is the case. Recognizing and addressing this linkage could affect some key interest groups in ways that would not provide incentive to change.

Drought impacts are experienced across a continuum of spatial scales, many of them at the scale of an individual person or household or small business. We have much less information at those scales and often have none. This applies to the causative physical factors as well as to the individual impacts. If we are lacking these local impacts, we are not in a position to aggregate upward and identify impacts that are cumulatively large but individually small. In part this difficulty stems from the difficulty of sampling to this level. Such sampling takes time, resources, skilled personnel, and coordination so that other analogous results can be compared and added. In general there are woefully few resources to address information needs at the local level. In addition, such capabilities vary widely from state to state; more uniformity is needed. This should be a priority of a national integrated approach to drought, such as with NIDIS (National Integrated Drought Information System). We are also lacking in mechanisms to record and track such information, but recent progress has been reported by the National Drought Mitigation Center in developing tools to assist with this cumbersome but important problem.

Until we can obtain comprehensive assessments of the full impacts of drought, across all scales, we cannot provide the documentation that decision makers often require to back up requests for utilization of public funds.

## MULTIPLE STRESSES

There are of course many factors at least as important as climate that govern whether there is enough water for a particular purpose. Trends in spatial distribution and numbers of people and population demographics greatly affect water use. There are many competing uses and needs for water by people (municipal and industrial, transportation, dilution and conveyance of waste, hydropower, recreation, traditional cultures) and by larger ecosystems (fish and wildlife, endangered species, silt deposition and delta health, benefits from flow fluctuation, marine and estuarine systems, delivery of fresh water affecting ocean circulation, nutrient transport and deposition). Water quantity and timing affect water quality. Each issue has optimal water flow and quality characteristics and requires that constraints be met for satisfactory function. These constraints cannot usually be both individually and collectively optimized simultaneously, thus requiring global optimization over all issues and thus compromises.

This is basically an issue of parts versus wholes. We can identify and describe each stress in great detail as a separate subject. It is when they combine that all sorts of interesting behaviors become possible. However, we should not lose sight of the fact that we deal with multiple stresses all the time and we generally make it through life anyway.

## COMPLEXITY AND NONLINEAR DYNAMICS

Because we have multiple stresses interacting at the same time, and because these interactions are highly nonlinear, we are in effect automatically preregistered in a giant experimental game from which we cannot withdraw. Emergent phenomena abound, and we should not be surprised to see unexpected or unpredictable things occur. We cannot say in detail what those are going to be; it is rather simply an issue that we should be prepared to be surprised at any time.

Because of this, it seems that the intertwined subjects of complexity, nonlinear dynamics, and chaos (and allied concepts) have a great deal to say about the generalized behavior we would expect to encounter. One of my own difficulties has been to try to discern where the knowledge we have gained about this subject can be supplied in some useful, practical, specific, or otherwise helpful way. In other words, where are the "insertion points" for the knowledge and insights developed by this field, in trying to cope with drought in a multi-stress environment? As with the stock market (itself a highly complex and nonlinear phenomenon), "past performance may not be an adequate predictor of future performance."

Many of our response mechanisms do not seem to adequately allow for low-probability, high-consequence phenomena that form part of the risk portfolio. What we really have is a large number of probability distributions (and some of them with heavy tails, such as precipitation) interacting in many ways, with nonzero odds of occasionally rather spectacular outcomes. By definition, we call these "surprises" but we should not be surprised (in a general way) to see (specific) surprises. We know they are likely to arise, but we do not know with any detail what they will consist of. The typical city fire department can be confident that a house will catch fire, but it cannot say which house. There are many military analogs, because in that arena many consequences of surprise are generally not favorable, but much thought and training are devoted to maintaining the flexibility to address them when they do happen.

Naturally we should try to anticipate as many types of outcomes from interacting stresses as possible, in a deterministic fashion, but it is simply hopeless to guess them all. Thus it is guaranteed that surprise will always be present.

All of this plays into our tendency to formulate management plans, and most especially, laws, that are unnecessarily (often in order to gain their approval) rigid and not reactive to new or developing information.

## BOUNDARY CONDITIONS AND INITIAL CONDITIONS FOR DROUGHT

By boundary conditions I am referring to the general circumstances "external" to a particular water balance determination, analogous to a boundary value problem in mathematics. In truth, in a connected system, there is hardly anything that is really "external," but that is being glossed over for now. As these conditions change, the degree or scope or other properties of some current drought situation are likely to be assessed differently. The history of how a current situation came into being may make a considerable difference as to what needs to be done, for two situations with similar current conditions.

One boundary condition that may not be stationary in time is demand, which is often proportional to population in some manner. A rather typical assumption made is that drought status is driven more by supply than demand. And it is true that the relative (annual) variation of precipitation is typically two to five times larger than the relative variation of evapotranspiration. The temporal variation of demand is not zero, however. In addition, population growth, at whatever rate, can, for example, negate assumptions about the stasis of a system of interest.

Groundwater contamination, as one example, can drastically alter supply, even if the source of contamination has been slowly building or gathering. A contaminated plume that is many years old may show up all at once. Groundwater flow through fractured media can exhibit many properties of Levy diffusion and related "burst" behavior. The impacts of such behaviors are often regarded as "surprises" and thus as pathologies, whereas a more careful analysis would have allowed for their possible existence.

Certain climate conditions (prolonged drought or prolonged moisture) can tip a system into a new "basin of attraction" in terms of state variables. For example, slow withdrawal from a water table can suddenly kill plant life when the roots can no longer reach deep enough. Hysteresis can then occur, because the reverse trajectory is not possible (dead plants do not become undead when the roots are reached as the water table replenishes). Slow changes in demand can make it more likely that some extreme condition occurs more often than before, increasing the likelihood that simultaneous occurrence of multiple extreme conditions takes a system to coordinates in state space that it has not hitherto visited.

## RATES MATTER

We are accustomed to the processes in various systems proceeding at certain ranges of rates. If sustainability is the goal, then there needs to be a matching of rates of supply versus demand, for all resources that are being consumed, or even merely used. In many cases groundwater withdrawal is occurring at far faster rates than the rates of aquifer recharge. This is especially true where we are mining groundwater that is hundreds or thousands of years old. Furthermore, recharge rates are highly variable and episodic in time (in various settings recharge can be steady or bursty), and in arid and mountainous environments especially, they are extremely variable in space, in both constant ways (mountains do not move, except in California) and time-dependent ways (monsoon thunderstorms, for example).

With systems that exhibit intermittent or bursty or transient behavior, the averaging time over which rates are computed can be very important. A heavy monsoon rainstorm in the desert may rain 5 inches per hour, but only for 10 minutes. The net effect of several such storms might later be expressed as "3 inches per year."

In addition, another rate comes into play. This is the rate at which our perceptions change as the circumstances in our vicinity change. Nearly all human beings live more in the past than in the present; we are always behind in our thinking. In an ideal world we would probably actually be living in a projected future (assuming we could do that correctly) and making our decisions from that perspective. But in reality our perceptions often lag the real situation because of learning times, communication delays, the need to spend time on other things, perhaps a certain unwillingness to be totally up to date, and the like. As an example, it seems likely that the typical native westerner is not fully aware of the full dimensions of sprawl in their favorite vicinity. Most of us are likely making decisions that reflect our understanding of how things were a minute or a week or a year ago, or two, or five, or 10, or 50. We probably could not cope if we endeavored to keep abreast of every development, so there may be elements of psychological defense mechanisms at work that have withstood the tests imposed by evolution.

The point here is that communication and the transmission of learning cannot occur instantly everywhere, every part of a system has imperfect knowledge of the status of the other parts, and the differences in such rates are a reflection of the contingent nature of history. These differences lead to differences in strategies for addressing whatever stresses are on the plate at the moment.

## SEQUENCING

The order in which things occur makes a difference. We have heard this from a number of drought and water managers. A single wet year in a sequence of dry years can yield much different overall consequences than if that wet year had been first or last. In some systems the drought clock can be partially or fully reset by a well-timed recharge. To help create a “worst case” scenario, the study in the early 1990s of severe and sustained drought on the Colorado River initiated the dry period with the lowest observed runoff years in succession.

Furthermore, the sequencing of different facets of climate can have great consequences, such as a particular moisture regime (wet or dry) accompanied or followed by a particular temperature regime (hot or cold). Insects, pathogens, and other pests often show spectacular responses to such combinations. The mormon crickets that have been prevalent in the northern Great Basin in recent years are favored or hurt by specific sequences of weather and climate anomalies. Drought and warm temperatures are permitting bark beetle behavior on an unparalleled scale in the northern Rocky Mountains of the United States and Canada in the last few years. For the latter, threshold factors, such as the ability to squeeze in two generations per year instead of one, are one example where highly nonlinear processes can qualitatively change the manner in which a system works.

Political action on complex problems is very often affected by essentially random accidents of timing.

## PREDICTABILITY AND PROBABILITY

With respect to the climate system, we have piecewise understanding of its internal workings, its current status, the status of boundary conditions, and the ability to model it to some level of accuracy. But all of these are imperfect. Some of these imperfections can be addressed through diligence and expenditure of resources, and others represent fundamental limitations inherent in what we *can* know. Predictions can be made better by improving the former, but are always subject to the limitations imposed by the latter. Prediction is only possible for patchy combinations of circumstances, and we can only know some of those combinations.

All of our understanding points to Nature as being fundamentally probabilistic. Thus, even though it is difficult, we should learn to work and think in this mode as much as we can. In particular, we should be thinking in terms of the probability distributions of our confidence in our observational database, and in the descriptions of how we model how the system evolves from one state to the next.

This represents a huge challenge for public education. In like manner, we have known about quantum mechanics for 80 years, but most of the public has a very poor understanding of this subject and does not even know it exists, even though it is the fundamental basis for how things function.

In atmospheric science, including both weather and climate forecasting, the ensemble approach has been increasingly applied and has resulted in better forecasts. This in effect constitutes a kind of poor man's method for sampling the possible states of a system, given the observations and the understanding of some of their error characteristics, and for sampling the physical parameterizations that represent how certain processes work. The same set of equations is run many times over but with random differences imposed on the input data, reflecting observational uncertainty, and in more complex approaches ("superensembles"), averaging across models that have a variety of approaches to parameterization of some particular process. The outcome of a typical set of forecast runs is that there are many possible solutions, with tendencies to cluster in certain ways. There are methodologies that can arrive at a consensus forecast but still retain the uncertainty and that furnish confidence information of value to other parties trying to utilize these results.

This ensemble methodology seems particularly valuable whenever there are a large number of degrees of freedom in a system. The climate system certainly has this property, and the drought/impacts "system" has far more than that. Furthermore, many of the latter are not subject to physical parameterization and are thus probably better described by using probability distributions. This method seems to offer many possibilities beyond the world of meteorology and climate where it originated and is still being refined.

The goal is to obtain better knowledge of the probability distributions of possible outcomes and assess what level of risk is attached to each outcome in the distribution. With this better understanding of what outcomes are possible, the costs and benefits associated with each outcome, and development of a weighted average outcome, can be evaluated. The net effect is that we do not end up making definitive and definite conclusions about what is or is not the case. We need to be neither too confident nor too diffident in what we believe, and we need probabilistic tools to help us with these assessments. Probabilities and risk-based approaches can lead to better decisions, including the tenacity with which we defend or suggest certain courses of action in the face of uncertain results.

The suggestion from this observer is that such approaches have the potential for reducing our usually undue confidence in the results we arrive at and the actions we recommend based on those results. This does not preclude the ability to utilize probabilistic guidance to help crystallize our thinking and make rapid, decisive, and definitive decisions when needed.

Some elements of this discussion were raised in the article "The Depiction of Drought: A Commentary," by Kelly T. Redmond, *Bulletin of American Meteorological Society,* 2002, 83(8):1143–1147.

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# DROUGHT MONITORING COMPLEXITIES IN THE WEST

*Philip Pasteris*
*U.S. Department of Agriculture*

"What can be learned about the impacts and interactions of multiple stresses from records of western U.S. precipitation and climate observations and their relation to drought and water supply forecasting?"

## BACKGROUND

*"The future ain't what it used to be." Y. Berra*

The western United States was built with, and is highly dependent on, water captured from mountain snowpacks that may be hundreds or even thousands of miles away from population centers and agriculture. The reservoirs built to meet the needs of agriculture, power generation, municipal water supply, and a variety of other uses were conceived, and in some cases built, nearly 100 years ago when populations were scarce, industry demand for power was in its infancy, and endangered species legislation did not exist.

The West's climate and mystique have lured settlers for over 150 years; however, it is ironic that drought was the genesis of one of the largest migrations during the 1930s. The population of the West was only 11.9 million in 1930 but grew 15 percent to 13.7 million by 1940 during the drought years. The West was able to absorb this increase; however, a pattern of western migration had begun. Significant reservoir construction from 1930 to 1970 resulted in increased water availability and inexpensive power, allowing irrigated agriculture, increased populations, and industry to gain a secure foothold.

Between 1980 and 2000 the population of the West grew 47 percent, from 42.2 million to 62 million, with no significant increase in water storage infrastructure. By 2002 agriculture represented 25.5 million western acres, generating an annual products-sold market value of $51.1 billion.

Recent energy prices have ignited interest in nonfossil renewable energy generation. Agencies such as the Bonneville Power Administration, which markets power produced from 31 federal dams in the Columbia Basin, have established operating plans based on climate and streamflow records for the period 1929-1978. Climate variability, combined with a projected 8 percent increase in regional firm energy demands, from an estimated 23,300 average megawatts in 2005 to 25,200 average megawatts in 2012 will have a direct impact on power availability and western economies. Columbia Basin hydroelectric dams, which rely on winter snowpack accumulation and spring and summer melt cycles, provide 73 percent of the region's energy (BPA, 2003).

## RECENT TRENDS IN WESTERN U.S. STREAMFLOW VARIABILITY AND PERSISTENCE AND POTENTIAL IMPACTS ON DROUGHT

Forecast streamflows and reservoir rule curves govern daily, monthly, and water year reservoir operations for power generation, navigation, flood control, and endangered species management. Many rule curves were developed using data from the middle of the past century and may not fully represent the recent streamflow trends and variability. A recent publication in the *Journal of Hydrometeorology*, "A Recent Increase in Western U.S. Streamflow Variability and Persistence" (Pagano and Garen, 2005), investigated trends in western U.S. streamflow. Variability and persistence can combine to amplify stress in drought-prone areas or, in extreme cases, produce drought in previously drought-free areas.

From the abstract: "April-September streamflow volume data from 141 unregulated basins in the western United States were analyzed for trends in year-to-year variability and persistence. Decadal time-scale changes in streamflow variability and lag-1 year autocorrelation (persistence) were observed.

"The significance of the variability trends was tested using a jackknife procedure involving the random resampling of seasonal flows from the historical record. As shown in Figure 1, the 1930s-1950s was a period of low variability and high persistence, the 1950s-1970s was a period of low variability and anti-persistence, and the period after 1980 showed high variability and high persistence. In particular, regions from California and Nevada to southern Idaho, Utah, and Colorado have recently experienced an unprecedented sequence of consecutive wet years along with multiyear extreme droughts.

"These various streamflow characteristics are not necessarily varying on the same time scales or coincidentally; increases in variability have preceded increases in autocorrelation by approximately 5-10 years, which have in turn preceded increases in skewness by another five years. Nonetheless, the various phenomena have become 'in phase,' making the most recent 20 years the only part of the record that is highly variable, highly persistent, and highly skewed. This triple alignment is perhaps the most challenging scenario for water managers. One possible scenario involves a series of consecutive wet years that overwhelm reservoirs and inflate stakeholder expectations about the amount of water available. An extended stretch of dry years exhausts storage reservoirs and does not give them a chance to recover. Smaller reservoirs that do not have multiple-year storage capacity would be especially vulnerable. In comparison, individual dry years interspersed among wet years are tolerable.

"These decadal oscillations also have implications for water supply forecasting. Statistical streamflow forecasting techniques that use persisted spring and summer streamflow as a predictive variable for next year's flows will lead the forecaster astray when the climate regime switches between positive and negative autocorrelation. The changes in persistence and variability are undoubtedly linked to changes in precipitation and temperature and not changes in basin char-

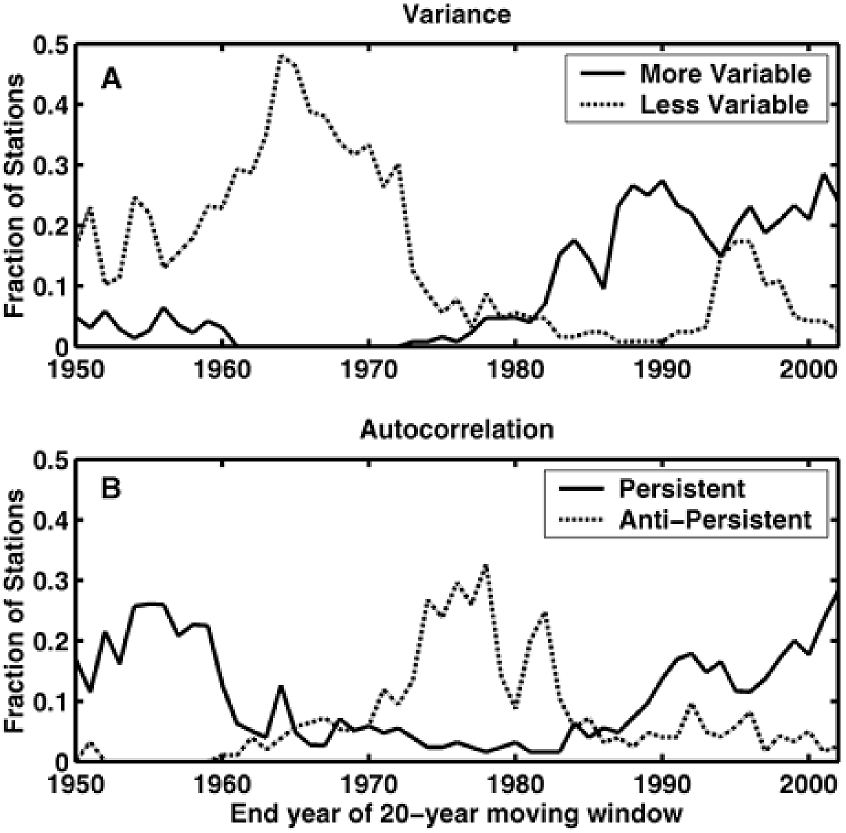

**FIGURE 1 A.** Time series of the fraction of western U.S. streamflow stations reporting statistically significant increases (solid) or decreases (dashed) in 20-year moving window variance compared to the period of record. **B**. Fraction of stations reporting lag-1 year autocorrelation of greater than 0.3 (solid) or less than –0.3 (dashed). All data are plotted at the end year of the 20-year moving window.

acteristics or soil properties. It is unknown at this time whether procedures that use antecedent autumn streamflow (e.g., September-November) as a predictive variable to index the effects of soil moisture are also vulnerable to this effect. The causes of the current triple alignment are unknown."

## SEASONALITY OF SNOWPACK AND DROUGHT IN THE WEST AND RECENT EVENTS

Recent publications by Mote (2005) highlight the shifts from traditional snow accumulation during the winter to a trend to warmer spring temperatures and declines in springtime snow water equivalent (SWE) in much of the North American West over the period 1925-2000, especially since mid-century. The Pacific Northwest has experienced two years of extremely low snowpacks in the past five years, 2001 and 2005. The 2001 snowpack deficits resulted in the second-lowest Columbia Basin streamflow on record, and the 2005 snowpacks, while not as low as 2001 basin-wide, did set new records in the Cascades of Washington and Oregon. In contrast to 2001 and 2005, an above-average snowpack on March 1 fell victim to record warmth and dryness over a two-month period (Pagano et al., 2004).

Warmer and wetter springs kick-start the growing season, and with potentially low snowpacks this can be problematic if water rights are called later in the growing season. The shift to earlier spring runoff in the West documented by Stewart et al. (2004) will pose challenges for water managers through the rest of this century.

After a six-year drought in the Great Basin, an enormous single-year snowpack recharged soil moisture and resulted in significant spring runoff. Is this an aberration, or will a long-term drought reestablish itself in the region? Can a probability of occurrence be quantified for the next water year? Can rapid shifts in climate from abundance to drought be forecasted with reliability? What will convince users that this can be done?

## DATA AVAILABILITY AND REQUIREMENTS FOR MONITORING DROUGHT, CLIMATE, AND WATER SUPPLY

The entire world has been transformed by the Internet. Within the last 20 years canary yellow teletype paper placed on a clipboard is now readily available for all to download and use. In the West, the SNOTEL data are downloaded several million times per year, giving customers the ability to develop and run site-specific or regional models to meet a wide variety of user needs beyond what can be done by traditional federal or state partners.

In addition to the Internet, affordable computers with spreadsheet and graphics software can replicate the work done in the past by mainframes.

## DATA GAPS

- Does a data gap really count if there is no need for the data (e.g., unpopulated areas, without agriculture)?
- What is a temporal gap? How often should a station report to meet user needs? Does technology support frequent observations?
- If data are poor, is that a data gap?

## SNOWPACK MONITORING

The SNOTEL dataset (~25 years) is a relatively new dataset compared to COOP network or paleo data, but it fills a very important vertical data void in the West. The oldest datasets (snow courses) are monthly or biweekly during the winter and extend back to the 1930s. Long-term snowpack records are a critical component of climate change research.

There is a critical need to provide quality control on all SNOTEL data. A project to provide quality control on SNOTEL temperature data will be completed in early 2006.

Remote monitoring is not cheap. SNOTEL sites require maintenance annually, or more often in some areas. A significant computer/communications investment is also necessary.

Plans to automate 900 manual snow courses with SNOTEL automation are in place and about a dozen snow courses or new sites/year are automated.

## WATER SUPPLY FORECASTING

Statistically based methods are still in use and provide reasonable results given the calibration dataset. However, statistical methods do not handle late-season events (heavy spring rains) or early-season forecasts during October-December due to lack of snowpack.

Improvements are underway to do a better job of visualizing the data and incorporating new prediction techniques. In addition, simulation modeling can help distribute flows during critical/extreme hydroclimatic events. Simulation models may require more real-time middle- and lower-elevation stations to properly represent hydrological conditions. In any event, “clean datasets” are needed to calibrate either model.

There is also a need to integrate climate forecasts with hydrological models to account for climate variability. This will be a challenge since the user community needs to understand the relationship of uncertainty between the climate and hydrological forecasts.

## SUMMARY COMMENTS

In conclusion, increased climate and streamflow variability present an ever-growing challenge to those who live in the West. Increasing population and its affect on land use, the growing need for electricity, environmental concerns, and the silent stress of a potential long-term drought hover over the desk of every resource manager. Understanding and learning from recent climatic and hydrological experiences can and will prove valuable in this new century.

## REFERENCES

Mote, P., A. Hamlet, M. Clark, and D. Lettenmaier. 2005. Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86(1):39-48.

BPA (Bonneville Power Authority). 2003. Pacific Northwest Loads and Resources Study—2003 White Book. (DOE/BP-3559).

Pagano, T., and D. Garen. 2005. A recent increase in western U.S. streamflow variability and persistence. Journal of Hydrometeorology 6(2):173-179.

Pagano, T., P. Pasteris, M. Dettinger, D. Cayan, and K. Redmond. 2004. Water Year 2004: Western water managers feel the heat. EOS, Transactions, American Geophysical Union, pp. 385-400.

Stewart, I., D. Cayan, and M. Dettinger. 2004. Changes in snowmelt runoff timing in western North America under a "business as usual" climate change scenario. Climate Change 62:217-232.

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# MULTIPLE STRESSES AND CLIMATE VARIABILITY: WHAT IF THE NEXT KATRINA IS A DROUGHT?

*William E. Easterling*
*Pennsylvania State University*

The importance of social and environmental processes as preconditions for drought is well established. Such processes are often mentioned in standard definitions of drought. What is missing, however, is a whole human-environment system approach to defining, monitoring, and measuring the frequency and intensity of droughts that takes into account underlying meteorological, hydrological, ecological, and sociopolitical processes.

For purposes of discussion it is reasonable to assume that droughts are ultimately triggered by scarcity of expected natural water supply, whether by precipitation deficiency, change in timing of snowmelt, inadequate groundwater recharge, or other forms of water shortage caused by climate variability. Multiple stressors are environmental and social processes or events that combine to dictate the limits to which an organism/individual, household, ecosystem, community, or region can absorb water scarcity before incurring unacceptable environmental or social cost. Stressors that influence the emergence and intensity of droughts can usefully be categorized as primary, secondary, and tertiary. *Primary stressors* are factors that directly influence water supply or demand across a range of scales. They may be environmental, as in the case of land cover change that increases evapotranspiration, or social, as in the case of rapid population growth or growth of water-intensive industry. *Secondary stressors* create conditions that abet vulnerability to water shortage, such as rural depopulation, decreasing agricultural comparative advantage, or high dependence on river-borne transportation. *Tertiary stressors* inhibit resiliency or adaptive capacity with respect to water deficiency. They also may be either environmental, as in crop and ecological diversity, or social, as in availability of risk management institutions, such as insurance networks and contingency planning. Adequate assessment of drought potential must consider not only climatological factors but also the full suite of interacting primary, secondary, and tertiary stressors.

Although anything but a drought, Hurricane Katrina clearly demonstrates the importance of multiple stressors interacting with a strong meteorological event. Katrina was the perfect storm more because of how it combined with a remarkable set of multiple stressors than its pure thermodynamic energy. It was a Category 4 (out of 5) hurricane that struck a city that arguably could not have been constructed to be more in harm's way. In addition to its elevation below sea level and the proven inadequacies of its levee and water pumping systems, the greater New Orleans region had become a critical port of entry for a significant percentage of the nation's imports, including natural gas, oil, and subsequent refinery products. Much of the midwestern grain produced for export passes through the port of New Orleans. This guaranteed that the impacts of Katrina would extend to the nation and the world. The large income divide separating New Orleans' wealthy and poor citizens left a large impoverished population especially vulnerable to the storm and its aftermath simply because it lacked the means to evacuate. Moreover, the translation of scientific assessments of hurricane vulnerabilities into practical political decisions did not happen. The list of multiple stresses at work in New Orleans was large, and their synergism with themselves and the hurricane surely intensified the loss of life and property and propagated impacts well beyond the region hit by the storm. An interesting question to ask is, What if Katrina had been the drought equivalent of a Category 4 hurricane occurring throughout the Mississippi River Basin—a sort of Dust Bowl II? What would we want to know about processes of social and environmental change that exacerbate precipitation deficiency? To try to answer this question might shed light on what we know and what we do not know about how multiple stressors might interact with a severe drought and in the process point out important research gaps.

Precipitation averaged about 20 percent lower and temperatures about 1°C higher than current during the decade of the 1930s in the central and western Great Plains. Were such an event to recur today, there are a number of stressors that likely would amplify the environmental and societal impacts. (In fairness, there are also improvements in resiliency due to learning from previous droughts that might provide some protection from a recurrence of the Dust Bowl droughts.) Some of the key stressors that intensified the destruction and damage of Katrina, ironically, would intensify the hardship of a long, severe drought. Table 1 lists a few examples of environmental and social situations and changes that would almost be certain to intensify the impacts of a superdrought in the Mississippi River Basin (MRB). As pointed out below, the reliance of the MRB on primary commodities and their water-borne transport renders the region vulnerable to any kind of climatic fluctuation that disrupts.

I am not aware of research that has explored how trends in multiple stressors, such as those listed in Table 1, affect the frequency or intensity of droughts. The closest vein of research is exemplified by O'Brien et al. (2004), who examined the vulnerability of Indian agriculture to climate variability and a small set of global stressors to determine the effects of being "double exposed." However, common sense suggests that rapid changes in one or more stressors that outstrip existing capacity to adapt to water shortage must, *ipso facto*, increase the frequency of dry events that become droughts. For example, the volume of barge traffic hauling corn down the Mississippi River to Louisiana for export increased at an annual average rate of 3.5 percent during the period 1972-1992. At the same time, the Pick-Sloan Missouri Basin Program calls for increasing water retention in the Missouri's Upper Basin to meet hydroelectric and environmental needs, thus cutting flows to the Lower Basin and Mississippi River. This nonlinear increase in barge traffic combined with less flow from the Missouri River during dry spells

**TABLE 1** Examples of Primary, Secondary, and Tertiary Stressors of Mississippi River Basin (MRB) Drought

Primary Stressors

- Basin-wide soil loss and subsequent sedimentation of navigation channels
- Over-pumping of High Plains aquifer leading to groundwater decline
- Increase in urban and municipal water demand caused by urban growth
- Water retention in major tributaries for irrigation, hydroelectric production, and in-stream environmental values
- Climate change

Secondary Stressors

- Invasive species, especially agricultural pathogens such as soybean rust in Gulf states
- Increasing volume of water-borne shipping of grain commodities
- Increasing debt:asset ratios on farms and crop price volatility combined with loss of comparative advantage
- Rising energy prices
- Diminished water quality
- Conflicting interstate water use policies (i.e., Pick-Sloan on the Missouri River Basin, Wyoming-Nebraska disputes over Platte River allocations)
- Aging of rural population

Tertiary Stressors

- Structural dependence on primary commodity industries
- Crop price support policies
- Alternative commodity transport systems
- Inadequate engineering designs of infrastructure, including channelization impacts on delta subsidence/inundation

suggests greater vulnerability of barge traffic, particularly in the lower MRB to once-minor low-flow events that now might constitute bona fide drought conditions. A recurrence of the 1930s droughts could be devastating to MRB agriculture, due to the direct impact on crop productivity and the diminished capacity to move grain to markets cheaply.

Multiple stresses must be accounted for in a comprehensive assessment of the potential frequency and magnitude of droughts. There are several research gaps that need to be addressed in this regard:

1. Improved understanding of how multiple stresses interact, both with themselves and climate variability, to influence vulnerability to water shortage;
2. Improved understanding of how adaptive capacity is influenced by multiple stresses;
3. Improved understanding of how multiple stresses and coping systems interact across different levels of scale (in space and time);
4. Using the understanding gained from 1, 2, and 3, whole human-environment analytical frameworks deployed with integrated assessment models, suites of leading indicators, and other comprehensive analytical methods are needed—the

USAID Famine Early Warning System (FEWS) could serve as a reasonable model;

5. Identification of coping system strengths (i.e., redundant response systems) and weaknesses (i.e., overburdened response systems); and

6. Stronger stakeholder involvement in whole human-environment system assessments to minimize exclusion of science-based risk analysis from applied risk management.

## REFERENCE

O'Brien, K. L., R. Leichenko, U. Kelkar, H. Venema, G. Aandahl, H. Tompkins, A. Javed, S. Bhadwal, S. Barg, L. Nygaard, and J. West. 2004. Mapping vulnerability to multiple stressors: Climate change and globalization in India. Global Environmental Change: Human and Policy Dimensions 14(4):303-313.

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# DROUGHT-INDUCED VEGETATION MORTALITY AND ASSOCIATED ECOSYSTEM RESPONSES: EXAMPLES FROM SEMIARID WOODLAND AND FORESTS

*David D. Breshears*
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***Woody plant mosaics are a key attribute of ecosystems***. A large portion of the terrestrial biosphere can be viewed as lying within a continuum of increasing coverage by woody plants (shrubs and trees), ranging from grasslands with no woody plants to forests with nearly complete closure and coverage by woody plants (Breshears and Barnes, 1999; Breshears, 2006). The characteristics of woody plants determine fundamental descriptors of vegetation types, including grassland, shrubland, savanna, woodland, and forest. Because woody plants fundamentally affect many key aspects of energy, water, and biogeochemical patterns and processes, changes in woody plant cover are of particular concern (Breshears, 2006).

***Drought can cause rapid changes in vegetation by triggering woody plant mortality.*** Assessments of potential global change impacts initially focused on how vegetation types matched given climatic envelopes. Later focus turned to how vegetation patterns might migrate with changing climate, focusing on rates of plant establishment. More recently, the importance of drought-induced die-off of woody plants was highlighted as a major dynamic response to climate variation and change. In particular, ecotones have been noted as areas where changes in vegetation in response to climate ought to be most rapid and responsive, as highlighted by a case study of vegetation response to drought during the 1950s (Allen and Breshears, 1998). In response to a severe drought in the southwestern United States during the 1950s, ponderosa pine (*Pinus pondersosa*) trees at lower, drier sites died, resulting in a shift of the ponderosa pine forest/piñon-juniper woodland ecotone of more than 2 km in less than five years (Figure 1) and producing a rapid change in vegetation cover (Figure 2). Similarly, within the distributional range for piñon pine (*Pinus edulis*), many trees at lower, drier sites within also died.

***Drought can trigger widespread tree mortality across a region.*** Although tree mortality almost certainly occurred across much of the Southwest in response to the 1950s drought (and probably for previous regional-scale droughts as well), few studies exist that allow scientists assessing impacts of drought to test predictions about the rapidity and extent of vegetation die-off response to drought. A recent drought beginning around the new millennium impacted the southwestern United States and was the most severe since that of the 1950s. Mortality of several species was observed throughout the Southwest. Mortality of piñon pine spanned

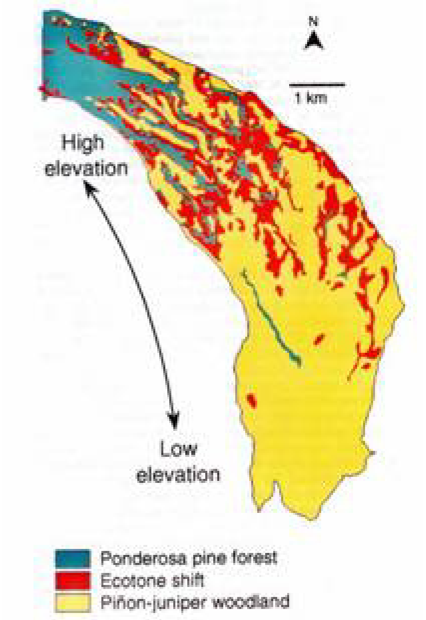

**FIGURE 1** An ectone shift. Changes in vegetation cover between 1954 and 1963 in Bandelier National Monument in northern New Mexico, showing persistent ponderosa pine forest (365 ha), persistent piñon-juniper woodland (1,527 ha), and the ecotone shift zone (486 ha) where forest changed to woodland in response to the 1950s drought (from Allen and Breshears, 1998).

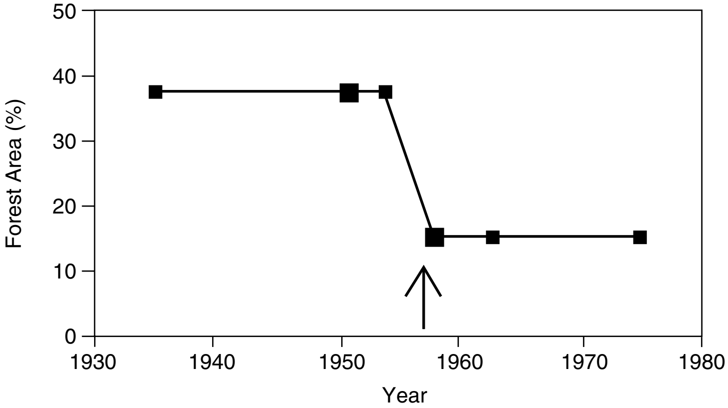

**FIGURE 2** A rapid reduction in forest cover. Changes in percent forest cover between 1935 and 1975 in Bandelier National Monument in northern New Mexico. The arrow indicates the time of historical observations of extensive tree mortality (from Allen and Breshears, 1998).

major portions of the species' range, with substantial die-off occurring over at least 12,000 km$^2$ (Breshears et al., 2005; Figure 3). For both droughts, die-off was related to bark beetle infestations, but the underlying cause of die-off appears to be water stress associated with the drought.

***Drought-induced tree mortality might be exacerbated under higher temperatures.*** The recent drought in the southwestern United States that triggered regional-scale die-off of piñon pine across the Southwest was not as dry as the previous regional drought of the 1950s (Breshears et al., 2005; Figure 4). However, the recent drought was hotter than the 1950s drought by several metrics, including mean, maximum, minimum, and summer (June-July) mean temperature. Tree mortality in response to the recent drought appears to have been more severe than that of the previous drought. In addition to die-off occurring across the region, the limited available data suggest that extensive piñon pine mortality

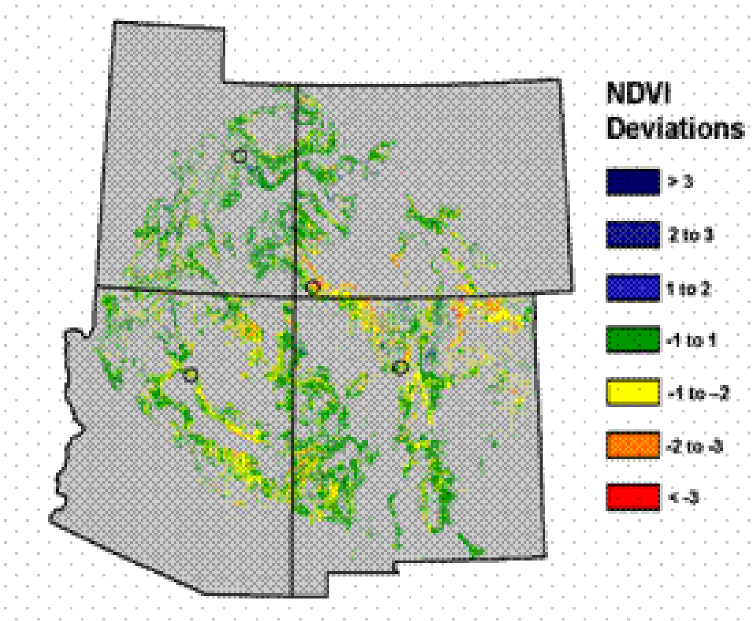

**FIGURE 3** Regional drought-induced vegetation changes. Change map for Normalized Difference Vegetation Index (NDVI) for region encompassing *P. edulis* distribution within Arizona, New Mexico, Colorado, and Utah, based on deviation from 2002-2003 relative to the predrought mean (1989-1999) during the period late May to June (Breshears et al., 2005). Changes in NDVI were linked to changes in foliar water content and plant water potential (Stimson et al., 2005) and to tree mortality at an intensively studied site within the region (from Breshears et al., 2005).

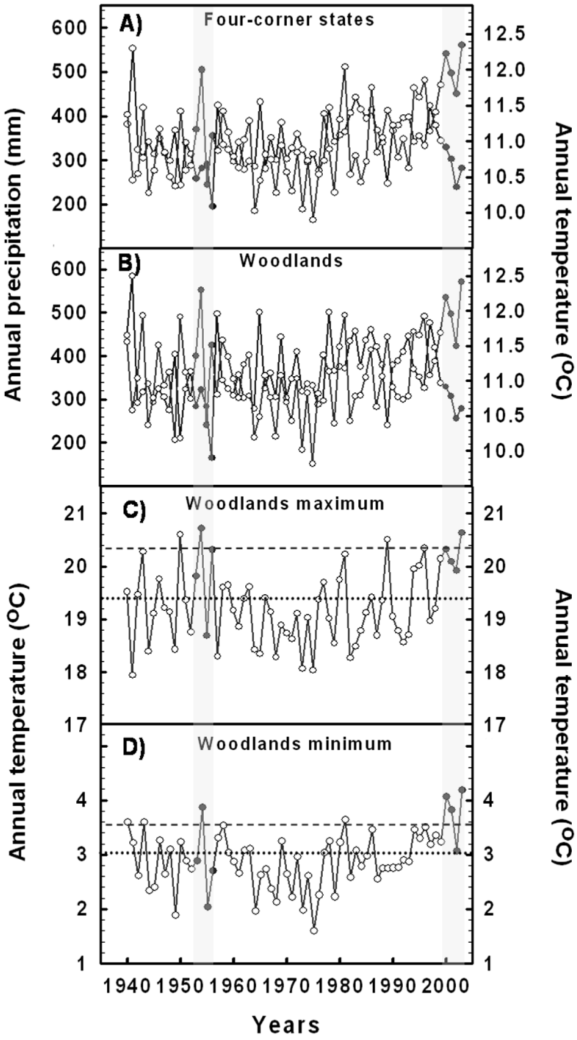

**FIGURE 4** A global-change-type drought. Southwestern North American climate. Annual mean precipitation (mm) and average of maximum and minimum temperatures (°C) for (A) all stations in the four-state region and (B) only stations in or near piñon-juniper woodlands within that region. Associated (C) maximum and (D) minimum temperatures for piñon-juniper woodlands (dotted line: long-term mean; dashed line: 10th or 90th percentile, differentiating driest or hottest years). Shaded bands are the four consecutive driest years of the 1950s drought (1953-1956) and the recent drought (2000-2003). Compared to the 1950s drought, the recent drought was wetter ($P < 0.05$) but warmer for maximum ($P < 0.05$) and especially minimum temperature ($P < 0.001$; from Breshears et al., 2005).

occurred at upper-elevation wetter sites in response to the recent drought but not in response to the 1950s drought. Hence, the warmer temperatures associated with the recent drought may have produced more extensive tree die-off. Because global change is projected to yield droughts under warmer conditions—referred to as *global-change-type drought*—the die-off from the recent drought may be a harbinger of vegetation response to future global-change-type drought (Breshears et al., 2005).

***Several other changes can accompany die-off of dominant overstory trees.*** In addition to the die-off of the dominant overstory tree species, other species underwent mortality in response to regional drought (Allen and Breshears, 1998; Breshears et al., 2005). These include juniper (*Juniperus monosperma*), a co-dominant with piñon pine for much of its range, and blue grama (*Bouteloua gracilis*), the dominant herbaceous species for many of these systems. Additionally, reductions in ground cover may contribute to an increase in erosion rates (Davenport et al., 1998; Wilcox et al., 2003). In particular, reductions in herbaceous ground cover might trigger a nonlinear increase in soil erosion once a threshold of herbaceous cover has been crossed. In addition, reductions in tree canopy cover can dramatically alter the distribution of near-ground energy (Martens et al., 2000). Therefore, die-off of overstory vegetation affects numerous key ecosystem processes that are dependent on incoming energy (Breshears, 2006).

***Drought-induced fire also triggers rapid canopy change and high soil erosion rates.*** Drought patterns can also trigger larger-scale fire patterns (Swetnam and Betancourt, 1998). Crown fire within woodlands and forests also can cause large reductions in tree canopy cover. Additionally, soil erosion can increase dramatically following forest wildfire (Johansen et al., 2001). The combined impacts of fire and drought-induced tree mortality are highlighted by the major changes in woodland and forest vegetation that have occurred in northern New Mexico over the past 50 years (Breshears and Allen, 2002; Breshears et al., 2005). It will be at least several decades following one of these types of disturbances before reestablishment of similar tree canopy cover in semiarid woodlands and forests could occur.

***Interactions among multiple effects of drought, including potential ecosystem cascades, remain major uncertainties requiring future research.*** Examples of drought-induced tree die-off in semiarid woodlands and forests highlight the rapidity and extensiveness with which drought can trigger vegetation change. Several nonlinear or threshold-like processes may occur and require improved prediction, including tree mortality, energy and water budget changes, and soil erosion thresholds. Systems can cascade through multiple states. For example, a location that had extensive ponderosa pine mortality in the 1950s had little reestablishment of ponderosa pine over the subsequent 50 years (Allen and

Breshears, 1998) and was within the region exhibiting extensive piñon pine mortality in 2002-2003 (Breshears et al., 2005); rates of soil erosion following the 1950s drought were and remain high. An ability to predict tree mortality, associated ecosystem responses, and effects on the carbon budget and on other ecosystem goods and services should be a high priority for future research (Breshears and Allen, 2002; Millennium Ecosystem Assessment, 2005).

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## REFERENCES

Allen, C. D., and D. D. Breshears. 1998. Drought-induced shift of a forest-woodland ecotone: Rapid landscape response to climate variation. Proceedings of the National Academy of Sciences U.S.A. 95:14839-14842.

Breshears, D. D. 2006. The grassland-forest continuum: Trends in ecosystem properties for woody plant mosaics? Frontiers in Ecology and the Environment 4:96-104.

Breshears, D. D., and F. J. Barnes. 1999. Interrelationships between plant functional types and soil moisture heterogeneity for semiarid landscapes within the grassland/forest continuum: A unified conceptual model. Landscape Ecology 14:465-478.

Breshears, D. D., and C. D. Allen. 2002. The importance of rapid, disturbance-induced losses in carbon management and sequestration. Ecological Sounding. Global Ecology and Biogeography 11:1-5.

Breshears, D. D., N. S. Cobb, P. M. Rich, K. P. Price, C. D. Allen, R. G. Balice, W. H. Romme, J. H. Kastens, M. L. Floyd, J. Belnap, J. J. Anderson, O. B. Myers, and C. W. Meyer. 2005. Regional vegetation die-off in response to global-change type drought. Proceedings of the National Academy of Sciences U.S.A. 102:15144-15148.

Collins, W. J., R. G. Derwent, C. E. Johnson, and D. S. Stevenson. 2002. The oxidation of organic compounds in the troposphere and their global warming potentials. Climatic Change 52:453-479.

Davenport, D. W., D. D. Breshears, B. P. Wilcox, and C. D. Allen. 1998. Sustainability of piñon-juniper woodlands—a unifying perspective of soil erosion thresholds. Viewpoint. Journal of Range Management 51:231-240.

Johansen, M. P., T. E. Hakonson, and D. D. Breshears. 2001. Post-fire runoff and erosion following rainfall simulation: Contrasting forests with shrublands and grasslands. Hydrological Processes 15:2953-2965.

Millennium Ecosystem Assessment. 2005. *Ecosystems and human well-being: Synthesis reports*. Washington, D.C.: Island Press.

Stimson, H. C., D. D. Breshears, S. L. Ustin, and S. C. Kefauver. 2005. Spectral sensing of foliar water conditions in two co-occurring conifer species: *Pinus edulis* and *Juniperus monosperma*. Remote Sensing of Environment 96:108-118.

Swetnam, T. W., and J. L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate 11:3128-3147.

Wilcox, B. P., D. D. Breshears, and C. D. Allen. 2003. Ecohydrology of a resource-conserving semi-arid woodland: effects of scale and disturbance. Ecological Monographs 73:223-239.

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# UNDERSTANDING AND MANAGING MULTIPLE STRESSES IN THE CONTEXT OF A COMPLEX RIVER BASIN: THE COLORADO RIVER

*Roger S. Pulwarty*
*NOAA/CIRES*

## WATERSHEDS, MULTIPLE STRESSES, AND STREAMS OF THOUGHT

Societies are always adapting incrementally and in diverse ways to a variety of integrated and cumulative changes. There is, however, little understanding of the long-term and widespread consequences of these adaptations at different levels of governance.

The "regional scale" has long been advocated as a useful organizational unit on which to coordinate and evaluate socially relevant research cognizant of geophysical, cultural, and jurisdictional boundaries. Yet attempts to manage consistent regional units of analysis, such as the watershed, have not met expectations. Difficulties arise in managing for particular outcomes given multiple contending perspectives and the uncertainties in variations and interactions between physical and ecological environments. The western United States offers and has offered unique opportunities for identifying lessons for strategic learning about the management of cross-scale environmental risks over time, particularly those associated with water. For example, droughts have played a major role in the evolution of western water institutions. Most notably, the droughts of 1865-1872 gave rise to prior appropriation law.

Gilbert White identified the major elements of integrated river basin development as follows: (1) multiple-purpose storage reservoirs, (2) basin-wide planning, and (3) comprehensive regional development. Studies of the first-order impacts of climate on each of these elements in the western United States indicate that vulnerability exists in the areas of storage and consumptive depletions versus renewable supply. Critical factors confronting sustainable resource use across western basins can be summarized under the following headings: population and consumption, water quality, environmental water allocation, uncertain reserved water rights, groundwater overdraft, outmoded institutions, aging urban water infrastructure, and evolving federal, state, and local relationships. Responses have included water banking, inter-basin transfers, advanced decision-support/expert systems, streamflow and demand forecasting, drought management programs, threshold indicators, and efficiency improvements.

The complications of changes in the spatial and temporal distribution of rainfall, soil moisture, runoff, frequency, and magnitudes of droughts and floods have not been explicitly included in response planning. Systems design, operational inflexibility, and legal and institutional constraints also reduce the adaptability of water systems and confound most recommendations to date on responding to climate change. Potential water-resource-related focusing events across the western United States include

(1) extreme and sustained climatic conditions (e.g., drought and floods);
(2) large-scale inter-basin transfers;
(3) quantification of tribal water rights;
(4) an energy crisis;
(5) changing transboundary responsibilities; and
(6) regulatory mandates such as the Endangered Species and Clean Water acts.

Critical thresholds arise when buffers are diminished and/or response curves steepen. A conspicuous aspect of water resources management has been the lack of careful post-audits of the social and economic consequences of previous programs and projects in the context of background variability and change. Three kinds of assessment questions may be asked: (1) What is known about the effects of past development programs on the environment? (2) What are, and how effective are, present programs (and their associated assumptions) in the context of a varying environment? (3) What appear to be the principal future effects of alternative adjustments? In this presentation we explore the above questions in one western basin, the Colorado, in which all of the above issues are exemplified.

## CASE STUDY: THE COLORADO RIVER BASIN

The Colorado River supplies much of the water needs of seven U.S. states, two Mexican states, and 34 Native American tribes, representing a population of 25 million inhabitants with a projection of 38 million by the year 2020. The Colorado does not discharge a large volume of water. Because of the scale of impoundments and withdrawals relative to its flow, the Colorado has been called the most legislated and managed river in the world. It has also been called the most "cussed" and "discussed" river. As has been well documented, the most important management agreement (the Colorado River Compact of 1922) was based on overestimation of the reliable average annual supply of water (estimated at 16.4 million acre feet) due to a short observational record. Colorado River streamflow however exhibits strong decadal and longer variations. The Colorado system also exhibits the characteristics of a heavily over-allocated or "closed water system." In such systems, development of mechanisms to allow resource users to acknowledge interdependence and to engage in negotiations and agreements is not only desirable but also necessary. Climate and weather events form a variable background on which these agreements and conflicts are played out. In this context institutional conditions that limit flexibility tend to exacerbate the underlying resource issues. This presentation describes how lessons from past events and new climate information on the Colorado River Basin inform or do not inform integrated watershed and adaptive management programs intended to preserve and enhance physical, economic, cultural, and environmental values. It begins with an overview of the history of Colorado Basin development and the scales of decision making involved. The decision-making environments are discussed in terms of critical climate-sensitive issues, including interbasin transfers and transboundary responsibilities, Native American rights, environmental requirements, and state water issues.

The Colorado system has experienced drought conditions in six of the last seven years. Until the last few years, the expectation of Colorado River managers was that significant shortages in the Lower Basin would not occur until after 2030. Events such as the drought expose critically vulnerable conditions and, though they warn of potential crisis, they also are opportunities for innovation. Historically, reservoirs and inter-basin transfers have been used to mitigate the effects of short-term drought in the Colorado Basin. The lessons and impacts of these adjustment strategies and more recent settlement agreements are still being gathered. The system's ability to maintain reliable supply during periods of severe long-term droughts of >10 years (the timescales of development, project implementation, and ecosystem management efforts), known to have occurred in the West over the past 1,000 years, is as yet untested but may be so in the very near future. While recent modeling studies project up to an 18 percent decrease in runoff in the basin under climate change scenarios, just the continuation of drought over the next year will likely induce crisis conditions. Thus the "normal" situation is critical. In the semiarid Southwest, even relatively small changes in precipitation can have large impacts on water supplies. Even in areas where integrated approaches are adopted, cooperation remains mainly crisis driven, inhibiting iterative, long-term collaboration and learning. While opportunities for "win-win" situations and rule changes exist, such changes are extremely difficult to implement. In this context institutional conditions that limit flexibility tend to exacerbate the underlying resource issues.

## OPPORTUNITIES FOR LEARNING AND DECISION MAKING UNDER UNCERTAINTY

Learning (and the capacity for employing lessons learned) is of strategic importance in the decades-long process of adapting to global changes, including climatic variations. Even when physical effects or projections can be established with fair confidence, there usually exist large uncertainties about biological and ecological effects and even greater uncertainties with respect to social consequences. Much work and experience has shown that long-term environmental problems can seldom be dealt with by single discrete actions or policies but respond only to continuing, sustained efforts at learning, supported by steady public attention and visibility. Focusing events provide opportunities for learning. In the West potential water-resource-related focusing events include:

(1) extreme climatic conditions (e.g., drought and floods);
(2) large-scale inter-basin transfers;
(3) quantification of tribal water rights;
(4) an energy crisis;
(5) changing transboundary responsibilities; and
(6) regulatory mandates such as the Endangered Species and Clean Water acts.

Crisis conditions can be said to be reached when focusing events occur concurrently with awareness of a finite time necessary for response. As mentioned above, for many basins in the West the normal situation is critical, and relatively small environmental changes can exceed social thresholds of acceptability and reliability.

Opportunities for learning also arise from deliberate perturbation (e.g., high flow releases) of a system to stimulate monitoring and learning. The idea of "adaptive management" has been widely advocated as a bridge between science and policy with a specific focus on ecosystems. This presentation explores the idea in the context of climatic and other uncertainties but grounds the discussion in the implementation of an actual adaptive management program in the Colorado. Adaptive management has three key tenets: (1) policies are experiments that should be designed to produce usable lessons; (2) it should operate on scales compatible with natural processes, recognizing social and economic viability within functioning ecosystems; and (3) it is realized through effective partnerships among private, local, state, tribal, and federal interests. In a watershed setting this can mean balancing hydropower production, habitat management, conservation, endangered species recovery, and cultural resources in order to experiment, learn, incorporate learning, and adapt—a decidedly idealized view. Each component carries its own type and sources of uncertainty. One goal is to identify the strengths and weaknesses of an "adaptive management approach" for mitigating drought risks in the context of changing climatic baselines and early warning in association with critical thresholds.

## CONCLUSIONS: IMPLICATIONS FOR DECISION MAKING

There is increasing awareness that we are engaged in (1) questions about the nature and role of integrated knowledge and uncertainty in complex settings and (2) a social process of risk communication and perception, as opposed to the simple development and dissemination of risk information or even a client-driven "two-way" process. The experience of development in the Colorado in the face of environmental uncertainty clearly illustrates that impacts and interventions can reverberate through systems in ways that can only be partially traced and predicted. In addition, adjustments and responses in the short term can increase vulnerability over the long term. The discussion here is based on the premise that understanding how effectively society might identify common goals, best use climatic and other information, and prepare for the consequences of future variations and surprises requires identification and evaluation of present systematic efforts (i.e., field-tested alternatives) to experiment, characterize uncertainties, make decisions, and cope with environmental variability across temporal and spatial scales. If lessons learned are to be applied, then a large part of the scientific goal should be to inform processes that can decrease impediments to the flow of information and innovations. This would entail:

(1) clarification of management goals at the human-environment interface;
(2) construction of a cooperative foundation between research and management;
(3) distillation of lessons from comparative appraisals of current and past practices;
(4) understanding and assessing adaptive capacity;
(5) characterizing and communicating uncertainties for both minimizing and managing risk; and
(6) developing effective criteria for validity and acceptability (i.e., robust information in research as well as practical contexts).

In this light a "seamless suite" of products and services for drought risk assessment and management, from national through local, may not be optimal in practice, especially if the goal is improvement of social welfare or at least informing the implementation of better decisions.

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# ECOSYSTEM-CLIMATE FEEDBACKS STUDIED WITH AN INTEGRATED GLOBAL SYSTEM MODEL

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The overall goal of our ecosystem-climate research program is to characterize and quantify the feedback mechanisms between terrestrial ecosystems, the climatic system, and air pollution involving the cycles of water, energy, and relevant chemical species. To address this goal we are developing and using an Integrated Global System Model (IGSM) that includes (1) dynamic and linked terrestrial hydrology and ecology, including the MBL Terrestrial Ecosystems Model (TEM); (2) comprehensive coupled physical climate (MIT two-dimensional atmosphere and three-dimensional ocean); and (3) MIT atmospheric chemistry (gaseous and aqueous phase chemical processes). The IGSM also includes a detailed global economics model, including emissions from industrial and agricultural activity. The integrated models represent the major complex biological systems on earth and span the scales from local to global.

With our coupled models we have quantified the combined effects of air pollution ($O_3$), rising $CO_2$, and climate change on the productivity and distribution of vegetation globally. We have also determined how changes in land ecosystems, caused by pollution and climate change, can feed back to climate through changes in carbon storage. We have calculated past and future carbon dioxide and methane fluxes from northern high latitudes under the joint influence of rising $CO_2$ levels and rising Arctic temperatures. We have also computed substantial changes in soil $N_2O$ emissions under the joint influences of changing temperatures, rainfall, and soil carbon. As the impacts of multiple stressors acting simultaneously on forest production are determined, their roles in amplifying or damping regional disparities are being elucidated. Toward these ends we have improved our Terrestrial Ecosystem Model and Atmospheric Chemistry Models to facilitate their interaction. We have also further developed our 3D Ocean Circulation Model to incorporate biogeochemical cycles. We also adapt the NCAR MATCH, CCM3, and CAM3 3D models for selected atmospheric chemistry studies. Our work is providing significant information for understanding how our future global environment will evolve under the joint effects of growing world population, changing technological and agricultural practices, and economic development. We argue that uncertainties in most of the relevant feedback processes are large. Therefore, to understand the above interactions we include comprehensive studies of the sensitivity of our conclusions to critical input assumptions, and calculations of the probability distributions of critical output variables. We address this through the use of multiple (ensemble) simulations, flexible models, and powerful (probabilistic collocation) methods to compute uncertainties. There are significant educational by-products of this research designed to effectively communicate results to students, fellow researchers, journalists, industry, and environmental policy makers. We are also making contributions to general methodologies to study and numerically simulate very complex and interactive spatially and temporally resolved phenomena using distributed memory computers. Much of our research has already appeared in multiple papers in *Journal of Geophysical Research*, *Tellus*, *Geophysical Research Letters*, *Climatic Change*, *Global Biogeochemical Cycles*, *Journal of Vegetation Science*, *Journal of Climate,* and other journals, and several papers are under review. Public access to our research, including reports and journal reprints, is available through our extensive websites: Joint Program on the Science and Policy of Global Change (*http://mit.edu/globalchange/*) and Center for Global Change Science (*http://mit.edu/cgcs/*).

Here we present the results of three of the projects.

## 1. INFLUENCE OF CLIMATE AND AIR POLLUTION ON ECOSYSTEM CARBON FLUXES

Several environmental factors influence carbon sequestration in natural terrestrial ecosystems, including climate variability and change, atmospheric carbon dioxide concentrations, ozone pollution, and atmospheric nitrogen deposition. To explore the relative importance of these factors on historical carbon sequestration, we have conducted a series of global simulations with a modified version of the Terrestrial Ecosystem Model. Model modifications include a more detailed representation of soil nitrogen pools and fluxes to better account for the influence of nitrogen deposition, nitrogen fixation, trace N gas emissions, and leaching losses of nitrate and dissolved organic nitrogen on terrestrial carbon and nitrogen dynamics. Initial results indicate that natural terrestrial ecosystems accumulated 54.8 Pg C during the 20th century as a result of $CO_2$ fertilization (39.2 Pg C), atmospheric nitrogen deposition (19.7 Pg C), and climate variability and change (3.1 Pg C); ozone pollution reduced the potential carbon sequestration benefits of these other factors by 7.2 Pg C. Over this time period, the rate of carbon accumulation increased from about 1.0 Pg C per year in the 1900s to 1.6 Pg C per year in the 1990s. Carbon sequestration is not uniformly distributed across the globe. Preliminary analyses also suggest that carbon losses associated with land use change over this time period would substantially reduce our estimate of carbon sequestration. Looking to the future, lowering of ozone levels resulting from future air pollution policies is estimated to increase carbon uptake by terrestrial ecosystems. To better account for the effects of human and natural disturbances, we are currently developing datasets and revising algorithms to consider the effects of agriculture, fire, logging, and insect infestations on terrestrial carbon and nitrogen dynamics.

## 2. CLIMATIC INFLUENCES ON METHANE SURFACE FLUXES

We have estimated fluxes by combining observations and models using (1) methane observations: high-frequency (13: AGAGE, CMDL, etc.) and Flask (41 comprehensive and 32 more intermittent: CMDL, CSIRO, etc.) monthly mean observations between 1996 and 2001; and (2) Global 3D MATCH model: interannually varying transport (NCEP) used with 1.8 deg. × 1.8 deg. resolution and 28 levels to create the $CH_4$ response of each site to monthly pulses from individual regional processes (sensitivity matrix). Using an annually repeating time/space-varying model OH tuned to AGAGE $CH_3CCl_3$ observations, the Kalman Filter is used to solve for seven seasonally varying processes (three wetland, three biomass burning, rice) as monthly varying fluxes; and two pseudo-steady processes (animals and water, coal and gas) as constant fluxes. Deduced interannual variability (monthly anomalies) is large with a 32-33 Tg/yr total emissions increase in 1998 coinciding with El Niño and global wildfires. Northern/tropical wetlands and rice region emissions dominate the total variability. Rice areas (including proximal wetlands) are responsible for 8-17 Tg/yr of this. Wetlands dominate the remainder, but boreal fires in Siberia may have also contributed to our deduced strong northern wetlands increase. Compared to previous estimates, energy-related emissions are smaller (decrease in Russia?) and emissions from rice-growing regions are larger (proximal forests or wetlands?). The computed seasonal flux cycles capture the expected seasonal cycles (but rice growing peaks earlier).

We have also used TEM to study how rates of methane ($CH_4$) emissions and consumption in high-latitude soils of the Northern Hemisphere have changed over the past century in response to observed changes in the region's climate. We estimate that the net emissions of $CH_4$ (emissions minus consumption) from these soils have increased by an average .08 Tg $CH_4$ $yr^{-1}$ during the 20th century. Our estimate of the annual net emission rate at the end of the century for the region is 51 Tg $CH_4$ $yr^{-1}$. Russia, Canada, and Alaska are the major $CH_4$ regional sources to the atmosphere, responsible for 64 percent, 11 percent, and 7 percent of these net emissions, respectively. Our simulations indicate that large interannual variability in net $CH_4$ emissions occurred over the last century. Our analyses of the responses of net $CH_4$ emissions to the past climate change suggest that future global warming will increase net $CH_4$ emissions from the Pan-Arctic region. The higher net $CH_4$ emissions may increase atmospheric $CH_4$ concentrations to provide a major positive feedback to the climate system.

## 3. CLIMATIC AND NUTRIENT IMPACTS ON NITROUS OXIDE EMISSIONS

Natural terrestrial fluxes of $N_2O$ from soils are important contributors to the global budget of this greenhouse gas. The IGSM incorporates the global Natural Emissions Model (NEM) for soil biogenic $N_2O$ emissions, which has

2.5° × 2.5° spatial resolution. It is a process-oriented biogeochemical model including the processes for decomposition, nitrification, and dentrification. The model takes into account the spatial and temporal variability of the driving variables, which include soil texture, vegetation type, total soil organic carbon, and climate parameters. Climatic influences, particularly temperature and precipitation, determine dynamic soil temperature and moisture profiles and shifts of aerobic-anaerobic conditions. The major biogeochemical processes included in the model are decomposition, nitrification, ammonium and nitrate absorption and leaching, ammonia emission, and denitrification. For present-day climate and soil datasets, NEM predicts an annual flux of 11.3 Tg-N (17.8 Tg $N_2O$). NEM predicts large emissions from tropical soils, which is qualitatively consistent with the observed latitudinal gradient for $N_2O$, and *in situ* flux measurements. Predicted emissions of $N_2O$ from runs of the NEM through 2100 indicate significant sensitivity to outputs from the climate (temperature, precipitation) and TEM (total soil carbon) models. Two NEM runs driven by climate outputs only and climate plus TEM outputs indicate that climate and soil carbon changes contribute about equally to the predicted very significant increase in $N_2O$ emissions. Since soil carbon and temperature are predicted to change in the future, the importance of including the feedbacks to climate forcing involving changing natural emissions of $N_2O$ is evident.

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# THE ROLE OF BIOGEOCHEMISTRY IN THE CLIMATE SYSTEM: EARLY EXPERIENCES FROM THE NCAR COMMUNITY CLIMATE SYSTEM MODEL

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## INTRODUCTION

The biogeochemical cycles of carbon, nitrogen, sulfur, and several other elements are integral components of the climate system that, until recently, have been neglected to a large degree in traditional physical climate studies. Perturbations to the planet's biogeochemical systems affect climate through changes in atmospheric composition, land surface properties, and ecological rates, which together in turn alter radiative balance and energy and water cycles. Several climate modeling groups have begun to include biogeochemical and ecological components into the coupled 3-D ocean, atmosphere, land climate models used to assess past, present, and future climate change. Here I discuss early results with the NCAR Community Climate System Model (CCSM). I focus on carbon-climate interactions resulting from anthropogenic fossil fuel combustion and climate warming as this example illustrates the complicated nature of the underlying coupled physical-biological interactions. I conclude with a brief overview of other biogeochemical processes being incorporated in the CCSM that may introduce important feedback mechanisms, nonlinearities, and thresholds to the climate system.

## CARBON-CLIMATE EXPERIMENT OVERVIEW

A new three-dimensional global coupled carbon-climate model is presented in the framework of the Community Climate System Model (CSM 1.4) (Doney et al., 2006). A 1,000-year control simulation has stable global annual mean surface temperature and atmospheric $CO_2$ with no flux adjustment in either physics or biogeochemistry. At low frequencies (timescale > 20 years), the ocean tends to damp (20-25 percent) slow, natural variations in atmospheric $CO_2$ generated by the terrestrial biosphere. Transient experiments (1820-2100) (Fung et al., 2005) show that carbon sink strengths are inversely related to the rate of fossil fuel emissions, so that carbon storage capacities of the land and oceans decrease and climate warming accelerates with faster $CO_2$ emissions (Figure 1). There is a positive amplification between the carbon and climate systems, so that climate warming acts to increase the airborne fraction of anthropogenic $CO_2$ and amplify the climate change itself. Globally, the amplification is small at the end of the

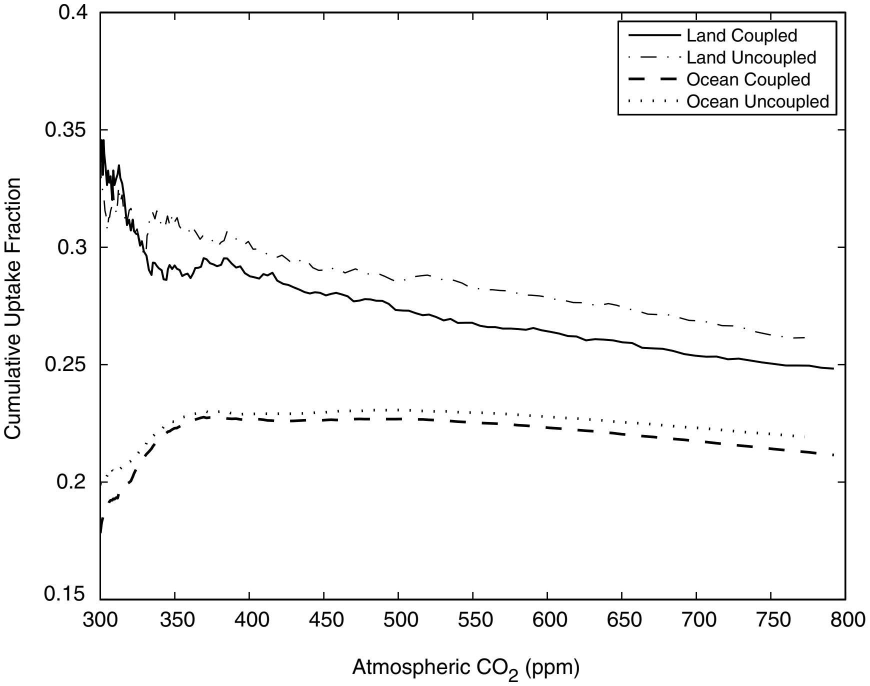

**FIGURE 1** Fractional uptake of anthropogenic $CO_2$ into land and ocean sinks as a function of atmospheric $CO_2$ concentration from transient simulation (1820-2100) using prescribed historical and SRES A2 $CO_2$ emissions. SOURCE: Fung et al., 2005.

21st century in our model because of its low transient climate response and the near-cancellation between large regional changes in the hydrological and ecosystem responses.

## MODEL DESCRIPTION

The physical climate core of the coupled carbon-climate model is a modified version of National Center for Atmospheric Research CSM1.4, which consists of atmosphere, land, ocean, and ice components that are coupled via a flux coupler. Into CSM1.4 are embedded a modified version of the terrestrial biogeochemistry model CASA, and a modified version of the OCMIP-2 oceanic biogeochemistry model. CASA follows the life cycles of plant functional types from carbon assimilation via photosynthesis, to mortality and decomposition, and the return of $CO_2$ to the atmosphere via microbial respiration. There are three live vegetation pools and nine soil pools, and the rates of carbon transfer among them are climate sensitive. The carbon cycle is coupled to the water cycle via transpiration and to the energy cycle via dynamic leaf phenology (and hence albedo). A terrestrial $CO_2$ fertilization effect is possible in the model because carbon assimilation via the Rubisco enzyme is limited by internal leaf $CO_2$ concentrations; net primary productivity (NPP) thus increases with external atmospheric $CO_2$ concentrations, eventually saturating at high $CO_2$ levels. The ocean biogeochemical model includes in simplified form the main processes for the solubility carbon pump, organic and inorganic biological carbon pumps, and air-sea $CO_2$ flux. New/export production is computed prognostically as a function of light, temperature, phosphate, and iron concentrations. A fully dynamic iron cycle also has been added, including atmospheric dust deposition/iron dissolution, biological uptake, vertical particle transport, and scavenging.

## NATURAL VARIABILITY

A sequential spin-up strategy is utilized to minimize the coupling shock and drifts in land and ocean carbon inventories. In the 1,000-year control, global annual mean surface temperature is ±0.10 K and atmospheric $CO_2$ is ±1.2 ppm ($1\sigma$) (Figure 2). The control simulation compares reasonably well against observations for key annual mean and seasonal carbon cycle metrics; regional biases in coupled model physics, however, propagate clearly into biogeochemical error patterns. Simulated interannual to centennial variability in atmospheric $CO_2$ is dominated by terrestrial carbon flux variability, ±0.69 Pg C $y^{-1}$, reflecting

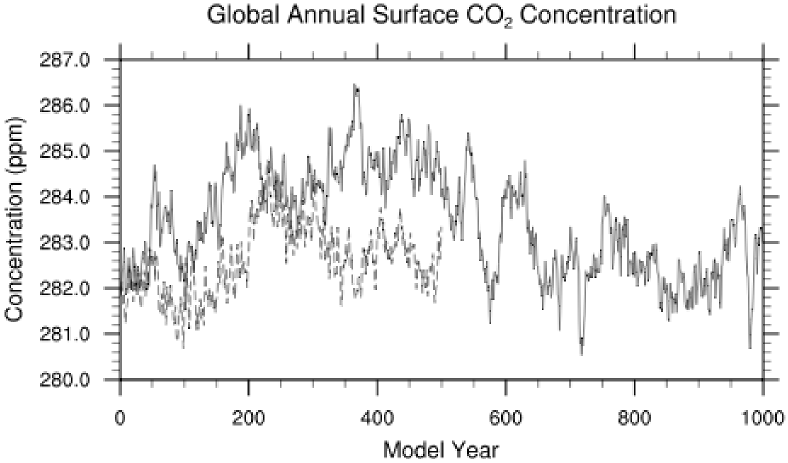

**FIGURE 2** Time series of global surface $CO_2$ concentration from CSM1.4 carbon control simulations. SOURCE: Doney et al., 2006.

primarily regional changes in net primary production modulated by moisture stress. Power spectra of global $CO_2$ fluxes are white on timescales beyond a few years, and thus most of the variance is concentrated at high frequencies (timescale < 4 years). Model variability in air-sea $CO_2$ fluxes, ±0.10 Pg C $y^{-1}$ ($1\sigma$), is generated by variability in temperature, wind speed, export production, and mixing/upwelling.

## ANTHROPOGENIC TRANSIENTS

Climate change is expected to influence the capacities of the land and oceans to act as repositories for anthropogenic $CO_2$ and hence provide a feedback to climate change. A series of experiments with the coupled carbon-climate model shows that carbon sink strengths are inversely related to the rate of fossil fuel emissions, so that carbon storage capacities of the land and oceans decrease and climate warming accelerates with faster $CO_2$ emissions. Furthermore, there is a positive feedback between the carbon and climate systems, so that climate warming acts to increase the airborne fraction of anthropogenic $CO_2$ and amplify the climate change itself. Globally, the amplification is small at the end of the 21st century in this model because of its low transient climate response and the near-cancellation between large regional changes in the hydrological and ecosystem responses. Analysis of our results in the context of comparable models suggests that destabilization of the tropical land sink is qualitatively robust, though its degree is uncertain.

## THE NEXT STEPS FORWARD

The preliminary treatment of the carbon cycle in CSM 1 is incomplete in many regards. For example, the terrestrial biogeochemical component neglects many of the factors thought to govern historical and future carbon sinks, such as land use changes, disturbance/fire, dynamic vegetation, and nitrogen limitation. Similarly for the ocean system, a number of other hypotheses have been proposed on how the planet's biogeochemical systems can alter climate and ecosystems. These include variability in ocean carbon storage driven by changes in atmospheric dust (iron limitation) and the impacts of ocean acidification on marine calcifiers (corals, pteropods, coccolithophores, etc.). All of these processes (along with reactive atmospheric chemistry) are being incorporated currently into a new version of the CCSM3. Plans are also underway, though at a very early stage, for including interactive human decisions, in effect moving CCSM toward a full earth system modeling capability.

## REFERENCES

Doney, S. C., K. Lindsay, I. Fung, and J. John. 2006. Natural variability in a stable 1000 year coupled climate-carbon cycle simulation. Journal of Climate 19(13):3033-3054.

Fung, I., S. C. Doney, K. Lindsay, and J. John, 2005. Evolution of carbon sinks in a changing climate. Proceedings of the National Academy of Sciences U.S.A. 102:11201-11206.

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# UNDERSTANDING ATMOSPHERE-BIOSPHERE INTERACTIONS: THE ROLE OF BIOGENIC VOLATILE ORGANIC COMPOUNDS

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Reactive biogenic volatile organic compounds (BVOC) have a substantial impact on air quality, especially ozone and particles, and the ability of the atmosphere to remove greenhouse gases, such as methane (Sanderson et al., 2003; Went, 1960). They are also a component of the carbon cycle that produces ~ 4 Pg of $CO_2$ each year (Guenther, 2002). These atmospheric chemical composition changes could perturb physical climate and the biosphere. Since BVOC emission rates are very sensitive to physical, chemical, and biological driving variables, they may have a significant role in earth system interactions and feedbacks, including those illustrated in Figure 1. However, these processes are complex, nonlinear, and difficult to predict given our current limited understanding. Increases in emissions of some VOCs are likely to result in increases of gases that can increase radiative forcing, but this would be accompanied by an increase in organic particles, which could decrease radiative forcing.

Although there are hundreds of different BVOC species emitted into the atmosphere, one compound (isoprene) contributes about half of the total annual global flux (Guenther et al., 1995). Other BVOC, such as β-caryophyllene, are particularly important for the production of secondary organic aerosol. There are ~ 50 BVOC chemical species that have an important role for atmospheric chemistry, either because they are emitted in large amounts or because they are particularly important for some atmospheric process (Guenther et al., 2000). BVOCs that have important ecological roles may differ from those with important atmospheric roles. For example, some BVOCs used as signaling compounds are present in the atmosphere at extremely low concentrations and have a negligible impact on the atmosphere.

## RESPONSE TO CHANGES IN ATMOSPHERIC CHEMICAL COMPOSITION

Isoprene emission rates are sensitive to atmospheric trace gas levels. Isoprene emission can increase when ozone is increased from background to levels representative of a polluted city (e.g., Velikova et al., 2005). However, this may not be sustained with long-term (months) exposure (e.g., Ennis et al., 1990). In addition, isoprene emission can decrease in response to an increase in $CO_2$ (e.g., Rosenstiel et al., 2003). However, this decrease is minimized when plants are grown at less than optimal soil moisture (Pegoraro et al., 2004).

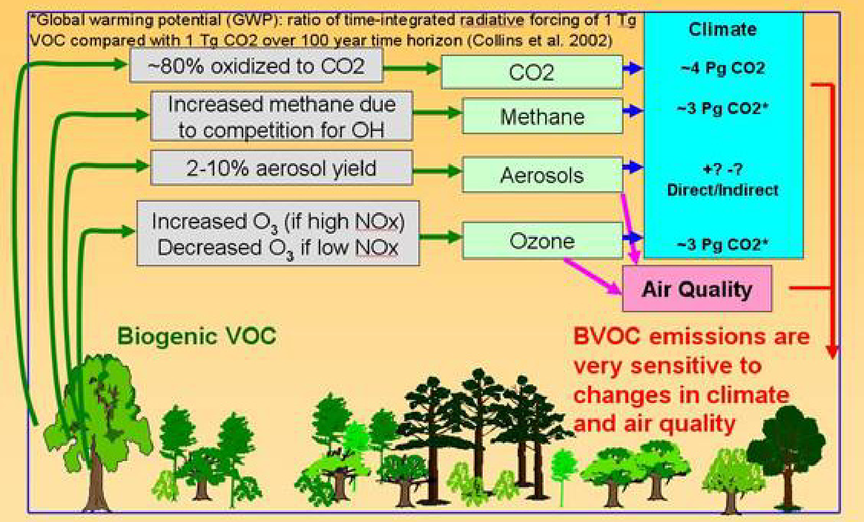

**FIGURE 1** The role of biogenic VOCs in biosphere-atmosphere interactions.

Very little is known about the potential impact of a changing atmospheric oxidation capacity on the use of BVOC signaling compounds for defense or attraction. The oxidation capacity of the atmosphere determines the lifetime of most BVOCs and so could limit the effective range over which organisms can use signaling compounds. The ecological implications of this change have not been quantified.

## RESPONSE TO CLIMATE CHANGE

Isoprene emission can be relatively insensitive to drought. Some studies show that a decrease in soil moisture that results in much lower photosynthesis and stomatal conductance can cause little or no decrease in isoprene emission until soil moisture reaches the point where photosynthesis ceases and the leaves begin to wilt (Pegoraro et al., 2004). There is occasionally even an increase, possibly due to increasing leaf temperatures associated with decreased transpiration. This may at least partly explain the surprisingly large seasonal variations in isoprene emissions that have been observed in tropical rainforests, which are the dominant global source of isoprene emission (Guenther et al., 1999). Isoprene emissions in the dry season can be a factor of 3 higher than during the wet season even after accounting for the known response of emissions to changes in temperature and solar radiation. The unexplained variations appear to be negatively correlated with soil moisture.

Isoprene emission is very sensitive to temperature and solar radiation. This is compounded by the ability of plants to adapt to changing temperature and light and results in even higher emissions associated with extended exposure to temperature and light (Guenther et al., 1999). As a result, a long-term 3K increase in temperature could result in an increase in isoprene emission of as much as a factor of 2.

## RESPONSE TO BIOLOGICAL CHANGE

Enclosure studies have shown that biological stresses (e.g., herbivory, fungal or viral infections, insect pests) can result in large increases in biogenic VOC emissions (e.g., Wildt et al., 2003). However, this phenomenon has not been investigated on canopy or landscape scales. Increasing levels of biological stress could be associated with future global change and would likely lead to elevated emissions of a variety of BVOCs.

Isoprene and other terpenoid emission rates from different plant species range across three to four orders of magnitude (Guenther et al., 2000). Landscape average emissions can vary more than an order of magnitude depending on plant species composition. On a global scale ~30 percent of all woody plants emit isoprene (Guenther et al., 1995). Isoprene emitters are found in a wide variety of landscapes, including tropical, temperate, and boreal ecosystems. There tends to be a higher abundance of isoprene emitters in disturbed (early successional) landscapes. In addition, many of the fast-growing tree plantation species (e.g, poplar, eucalyptus, oil palm, rubber tree) have extremely high isoprene emissions (Guenther et al., 2000). Large monoculture plantations of these species will likely have a dramatic impact on local air chemistry.

## REFERENCES

Ennis, C. A., A. L. Lazrus, P. R. Zimmerman, and R. K. Monson. 1990. Flux determination and physiological response in exposure of red spruce to gaseous hydrogen peroxide, ozone, and sulfur dioxide. Tellus Series B-Chemical and Physical Meteorology 42B:183-199.

Guenther, A. 2002. The contribution of reactive carbon emissions from vegetation to the carbon balance of terrestrial ecosystems. Chemosphere 49(8):837-844.

Guenther, A., C. N. Hewitt, D. Erickson, R. Fall, C. Geron, T. Graedel, P. Harley, L. Klinger, M. Lerdau, W. A. Mckay, T. Pierce, B. Scholes, R. Steinbrecher, R. Tallamraju, J. Taylor, and P. Zimmerman. 1995. A global-model of natural volatile organic-compound emissions. Journal of Geophysical Research-Atmospheres 100(D5):8873-8892.

Guenther, A., B. Baugh, G. Brasseur, J. Greenberg, P. Harley, L. Klinger, D. Serca, and L. Vierling. 1999. Isoprene emission estimates and uncertainties for the Central African EXPRESSO study domain. Journal of Geophysical Research-Atmospheres 104(D23):30625-30639.

Guenther, A., C. Geron, T. Pierce, B. Lamb, P. Harley, and R. Fall. 2000. Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America. Atmospheric Environment 34(12-14):2205-2230.

Pegoraro, E., A. Rey, R. Murthey, E. Bobich, G. Barron-Gafford, K. Grieve, and Y. Malhi. 2004. Effect of $CO_2$ concentration and vapour pressure deficit on isoprene emission from leaves of *Populus deltoides* during drought. Functional Plant Biology 31(12).

Rosenstiel, T. N., M. J. Potosnak, K. L. Griffin, R. Fall, and R. K. Monson. 2003. Increased $CO_2$ uncouples growth from isoprene emission in an agriforest ecosystem. Nature advance online publication, January 5 (doi:10.1038/nature 01312).

Sanderson, M. G., C. D. Jones, W. J. Collins, C. E. Johnson, and R. G. Derwent. 2003. Effect of climate change on isoprene emissions and surface ozone levels. Geophysical Research Letters 30(18):1936, doi:10.1029/2003GL017642.

Velikova, V., P. Pinelli, S. Pasqualini, L. Reale, F. Ferranti, and F. Loreto. 2005 Isoprene decreases the concentration of nitric oxide in leaves exposed to elevated ozone. New Phytologist 166(2):419-426.

Went, F. W. 1960. Blue hazes in the atmosphere. Nature 187(4738):641-643.

Wildt, J., K. Kobel, G. Schuh-Thomas, and A. C. Heiden. 2003. Emissions of oxygenated volatile organic compounds from plants. Part II: Emissions of saturated aldehydes. Journal of Atmospheric Chemistry 45(2):24.

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# HUMAN-EARTH SYSTEM INTERACTIONS

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The societal relevance of understanding complexities of earth system interactions is that human activity both affects these systems and is affected by changes in them. The goal of our research in this regard is to understand the complex and dynamic interactions between human and earth systems at the global scale, but resolved regionally. Our approach is to link a global model of the world economy, the Emissions Prediction and Policy Analysis (EPPA) model, with a comprehensive model of terrestrial hydrology and ecology and the physical climate system as controlled by atmosphere and ocean processes as they interact with terrestrial systems. At present, the physical and ecological system is resolved at a level that has come to be known as an earth system model of intermediate complexity, with less spatial resolution than a full-scale 3-dimensional Atmosphere-Ocean General Circulation Model (AOGCM) but with far more detail than the highly parameterized energy-balance-type models that have been widely used in integrated assessment. We sacrifice further resolution in the modeling of individual components of the earth system so that the Integrated Global System Model (IGSM) is computationally efficient, allowing us to evaluate very large ensemble runs (order $10^2$-$10^3$). The desire to produce large ensemble simulations is driven by our interest in understanding the phenomenon of global environmental change as one of risk management. Research and modeling of the interaction of physical and ecological earth systems is described by Prinn (2006) and in greater detail in Sokolov et al. (2005).

The standard approach for evaluating the economics of climate change, or many policy problems, is to study the policy issue in isolation, focusing on the efficiency of economic instruments and calculation of an optimal policy. In contrast, our approach has been to explicitly recognize that economic systems are complex: multiple economic and environmental problems interact and these interactions strongly affect the efficiency and effectiveness of policy instruments and lead to very different conclusions than one would obtain absent this more realistic representation of economic activity and its relationship to the natural environment. In this regard, it is useful to consider three broad sets of complex interactions. Those among: (1) economic policies directed toward different economic problems, (2) the economy and the changing set of technological options as they affect abatement potential and cost, and (3) the economy and the physical-ecological earth system. And, in fact, there are strong interactions among all of these categories. Thus, the simplifying assumptions often made in research to allow separate study of just the economic system, a single country or sector, or climate in isolation of other economic issues are invalid. Whether these complexities strongly affect conclusions one might reach of viable policy options is a major focus of our ongoing research program. Published research appears in journals such as the *Journal of Environmental Economics and Management*, *The Energy Journal*, *Energy Economics*, *Environmental Modeling and Assessment*, *Climatic Change*, *Science*, *Nature*, *Energy Policy*, *Climate Policy*, and others. A description of the EPPA component and the IGSM and freely available reports and reprints are on the Joint Program on the Science and Policy of Global Change website, *http://web.mit.edu/globalchange/www/*. Here, I would report very briefly some results from our program on each of the three sets of interactions above, to illustrate how modeling the complexity of the system leads to different results than one might otherwise expect. This is not intended to be a comprehensive review of these topics as in many cases there is a considerable body of accumulated research.

## COMPLEX INTERACTIONS AMONG ECONOMIC POLICIES

In an idealized economy the prices of goods reflect the marginal cost of producing them, and consumers who base decisions on these prices equate their marginal value of use of the good to these prices. The widely demonstrated result in neoclassical economics is that the equalization of marginal cost and marginal value through a price system, in this idealized world, results in an optimal use of resources. Environmental economics adds to this issue, by observing that an environmental problem like climate change is an "externality" in that, absent a specific climate policy, there is no price paid for disposing of greenhouse gases in the atmosphere, prices of goods and services that emit them thus do not reflect the damages associated with emissions, and emissions and consumption of emission-intensive goods are too high. In the idealized economy, one finds a strong theoretical result that an economic instrument that prices carbon abatement equally across sectors and regions is "cost effective" in the sense that it achieves that level of reduction at the least cost, and "optimal" or "efficient" if the carbon price is also determined to be equal to the marginal benefit in terms of reduced damage.

There are many widely recognized ways in which real-world economies depart from the idealized neoclassical economy. This recognition is hardly new; it was formulated in the 1950s as the "theory of the second best" and also has had implications in international trade where it was described as the paradox of "immiserizing growth." For a review of these issues, see Babiker et al. (2003a). Violations of the idealized economy are variously described as preexisting distortions (other taxes that do not reflect a specific externality), externalities (other than the climate change itself) that are not priced at all or are mispriced, and cases where actors in the economy are large enough to affect prices and this affects (or should be considered) in their decisions. The tax system of an economy is one important distortion, and important interactions of climate policy and tax policy have led to findings showing a "double dividend" for the U.S. under some cases, but we have found that this does not necessarily translate to other countries because it depends on the specifics of the tax system, so a double dividend was less likely to exist in many European countries (Babiker et al., 2003b). We have also shown that divergence from an economy-wide cap and trade system may be economically superior to a cap and trade system that equalizes the marginal cost of carbon across sectors (Babiker et al., 2004). This has further implications for international permit trading, where we find that autarkic compliance with a cap may be economically superior to an international permit trading system (Metcalf et al., 2004). This can be traced to the relative level of taxation of fuels (Paltsev et al., 2004). A further implication is that simple models where the carbon permit price (marginal abatement cost) is taken as an indicator of the cost of the carbon policy can be highly misleading. For example, the double dividend finding is one where it is possible that, by recycling revenue from a carbon tax to offset existing distortionary capital and labor taxes, the carbon policy has a marginal social benefit quite apart from any climate damage avoidance (Babiker et al., 2003a). In other cases interaction of the carbon policy with existing energy taxes can lead the average social cost of the carbon policy to be on the order of five times higher than the marginal carbon reduction cost (Paltsev et al., 2004). Agriculture/land use is an important source of emissions and/or a potential sink particularly in developing countries (Hyman et al., 2003) and is a sector with extensive policy intervention (preexisting distortions). Research on the interactions of climate policy and agricultural policy has been limited or nonexistent to date, but accurate representation of the agriculture sector and policies is needed to capture the interactions between climate and other policies that affect agriculture. Obviously, agriculture is also a sector sensitive to environmental change, and so that interaction among agricultural policies and the natural environment itself is essential.

## INTERACTIONS BETWEEN THE ECONOMY AND CHANGING TECHNOLOGY

A description of the global economy embodied in a computable general equilibrium model such as our Emissions Prediction and Policy Analysis (EPPA) model represents explicitly or implicitly the technological options open to the economy over time (Jacoby et al., 2006; Paltsev et al., 2005a). Much effort has been invested in the research community to develop endogenous models of technical change, recognizing that price or other economic signals resulting from a climate policy would likely change the pace and direction of innovation. Here, one must realize that the task of endogenously describing technical change requires the modeler to describe all possible blueprints of relevant technologies and their ultimate cost and the cost of discovering them. Essentially this demands the modeler to know the details of technologies ahead of those who are working to discover them. While this is an impossibility—if we knew it we would not have to discover it—there are worthwhile avenues of research. Our approach has been to first describe the current state of technological options, and examine their changing potential as resource availabilities and prices changed, as in the case of carbon sequestration (Jacoby et al., 2006). While at the time this research was being done, natural gas combined-cycle technology was seen as the dominant technology and thus the likely future in a carbon-constrained world, we found that rising gas prices would likely mean that integrated gasification of coal with sequestration was much more promising in the longer run. Gas prices have since risen dramatically, and this result would now surprise no one, but the only hope of escaping whatever the current mindset with regard to prices is to try to represent underlying fundamentals of demand and resource availability. We have further explored the value of carbon sequestration in oceans, recognizing that ultimately the carbon will end up in the ocean anyway, so that it was properly investigated as "temporary storage" (McFarland et al., 2004). This work found that there could be no value to temporary storage, and any value depended on the existence of a backstop that would cap the price of carbon or include a damage function and optimal carbon price that would likely mean ever-increasing atmospheric carbon levels. Modeling the explicit technological options where there are diverse technological options such as transportation can be daunting (Schafer and Jacoby, 2003), with the need to consider the evolution of demand, changing technological options, and interactions with existing policies such as fuel taxes (Paltsev el al., 2005b).

Important in the issue of trying to represent technical change is to represent the resources in the economy that are devoted to innovation and the fact that allocating these resources to climate change mitigation (or adaptation) means reallocating them away from other research endeavors (Sue Wing, 2003). In recent work, we are following up on preliminary investigations (Jacoby et al., 2006) to unravel the processes at work that may explain why technologies penetrate in the classic S-shape and exhibit declining costs. Several processes are at work, including vintaging/irreversibilities in the capital stock for the existing technology, adjustment costs due to rapid scaling up of the capacity to produce the new technology, monopoly rents associated with at least initially unique skills/knowledge and possibly enforced through intellectual property rights laws, and finally the innovation/learning process which may contribute to improvements in the technology. The technology may also depend on a resource that is varied in quality and is more or less accessible (e.g., wind or solar) or competes with other uses (e.g., biomass competition with food for land). Different combinations of these phenomena can lead to S-shaped penetration and/or declining cost. Much work has focused on learning curves, assuming the declining cost reflects innovation. Such relatively simplistic analyses would suggest that subsidization or other stimulation of the market will push the technology cost down a "learning curve," but this can be misleading to the extent other processes are at work. Our preliminary results suggest that subsidization can lead to waste by increasing adjustment costs if that is the primary explanation, extra profits with no improvement in the technology if monopoly rents are the primary explanation, or advance of the technology if learning explains the falling costs.

Key to modeling technical change is to recognize that knowledge is itself a problem for neoclassical economics because the marginal cost of using knowledge, once discovered, is zero, but pricing knowledge at zero does not compensate for the cost of discovering it, thus the existence of intellectual property rights protection that tries to balance compensation for innovation through granting of monopoly rights with economic efficiency of making the technology widely available. Also, there are typically knowledge spillovers so that even with the patent protection, developers may never fully capture the returns to investments. With some advocating a technology policy to solve the climate problem, careful examination of these complex issues is critical. In one study of the Dutch economy a fully dynamic, forward-looking, multisector general equilibrium setting, including technology spillovers examines this issue (Otto et al., 2006). In this study, effective technology policy can increase the needed carbon price and the economic cost of climate policy in absolute terms, albeit the economy is much larger with effective technology policy than without. We have found a similar result in a much simpler framework, where we imagine that, exogenously, gas resources are much larger than any conventional estimate. One might expect this to lead to substitution away from coal, oil, shale oil, and the like, thus reducing emissions of $CO_2$. Instead, $CO_2$ emissions increased, again because the growth effect of lower gas prices dominated the substitution effect. Similarly exogenous bias toward growth of the service sector—while reducing emissions somewhat compared with the case of neutral growth in sectors—has a much smaller effect than one might expect given the low energy intensity of the sector because of the interindustry demands of the service sector for relatively energy intensive goods and services (e.g., transportation). While initially surprising or counterintuitive, there is an intuition behind these results, and they suggest the need for consideration of the complex interactions of technical change, growth, and climate policy.

## INTERACTIONS BETWEEN THE ECONOMY AND THE PHYSICAL-ECOLOGICAL EARTH SYSTEM

The grand statement of the problem of interaction of the economy and the physical-ecological earth system is the formal statement of the global warming potential index issue, extended beyond the conventional greenhouse gases to other pollutants and beyond warming to the direct or other effects of substances of concern (Reilly and Richards, 1993; Reilly et al., 2003). The objective function in this problem is to minimize the burden on the economy taking into account the cost of controlling various greenhouse substances and the damage they cause. This is an exceedingly demanding research agenda in that it requires valuation of the multiple effects of global warming (crops, health, extreme events, ecological disruption), the multiple effects of greenhouse substances ($CO_2$ fertilization, damaging effects on vegetation and health of tropospheric ozone and of aerosols), the varying costs of abatement of different substances, and the complex interactions (in the atmosphere due to chemistry, in mitigation cost due to shared generating processes, and feedbacks such as environment on carbon uptake). We have considered this starting from a relatively complete description of shared generating processes and well-articulated model of the complexity of atmospheric chemistry to show that the 100-year GWPs undervalue methane abatement substantially (Reilly et al., 1999). We have studied this within the context of a forward-looking economic model with climate damages explicitly valued to study the implications of alternative representations of the discount rate, finding that if the declining discount rate formulation some have proposed for long-term problems is correct, then concern shifts to the very long-lived substances (Reilly et al., 2001). And again we used the more fully articulated physical model to show that under a policy to stabilize $CO_2$ at 550 ppm the effects of undervaluing methane using GWPs persists for 250 to 300 years (Sarfim et al., 2005). And most recently we have examined the effects of common air pollutants on climate as already discussed by Prinn showing countervailing effects at least in terms of global mean surface temperature changes (Prinn et al., 2006).

A recent focus is on the feedbacks of changing environment on the economy itself. We have showed that tropospheric ozone could significantly reduce carbon uptake by vegetation and thus increase the cost of meeting a 550 ppm stabilization target by 6 to 21% (Felzer et al., 2005). The surprisingly large cost addition results from valuing the cost change at the margin. We have also evaluated multiple environmental changes (climate, $CO_2$, $O_3$, and consequent changes in soils) on agricultural crops and the economy. This shows significant current ozone damage in the United States, Europe, and China (4-9% loss of the value of crop production), and the potential for this loss to increase substantially even if ozone precursors are controlled (Reilly et al., 2004, 2006). At the same time, this shows a generally beneficial effect of climate/$CO_2$ largely driven by the positive $CO_2$ fertilization effect. We find that the agricultural sector "adapts" almost completely to these changes in terms of the production effect, but that the economic effect is measured in other sectors as resources shift into or out of agriculture. So, the cost of adaptation, in terms of % loss of the value of crop production, is about ½ the direct yield loss even though production changes very little in response to fairly severe productivity shocks. Notably, international trade has effects across different regions because of the differential productivity effects. We have also examined the health effects of air pollution and the resultant effects on the economy. So far we have focused on the United States and, preliminarily, China (Yang et al., 2005; Matus et al., 2006; Matus, 2005), finding a substantial remaining burden of air pollution on the economy, particularly of China, where the remaining burden is estimated at 10% of macroeconomic consumption. Our interest in this work is to complete the modeling of feedbacks on the earth system. Effects on agriculture, and changing production and trade, mean changes in land use in producing regions, with consequent effects on the biogeochemical cycle. Abandonment of land, or reduced intensity of use, would mean increased carbon uptake, while expansion of intensified use would likely lead to release of carbon and other greenhouse gases. We expect important interactions with mitigation options, in particular biomass energy that competes for land and is similarly affected by environmental change. Air pollution health effects, through their effect on the economy, may also affect emissions, but we are also interested in joint policy solutions whereby a climate policy may affect health via its effect on air pollution emissions, or conversely air pollution policy driven by the desire to reduce health effects may lead to changes in climate.

An important goal for us with regard to analysis of impacts is to value damages in a manner consistent with mitigation costs to make for a more consistent comparison of benefits and costs. Mitigation cost analysis works on a rich theoretical and empirical basis, developed as computable general equilibrium models that can be simulated dynamically. Damage assessment can be extremely *ad hoc*, multiplying a constant wage rate or value of life times an estimate of hours or lives lost. In this regard, one of the early findings is that even though pollution levels can fall over time, the absolute damages may rise over time because real wages and other prices rise. We also find significant improvement of damage estimates through modeling of the accumulation effect of chronic exposure to air pollution. The methods we have developed for estimating impacts are based on the same rich theory and empirical foundation as mitigation costs, and we have now set in place satellite physical accounts for land, energy resources, and population (Asadoorian, 2005) so that we can dynamically link this theoretically based economic model with earth system components.

## REFERENCES

Asadoorian, M. O. 2005. *Simulating the Spatial Distribution of Population and Emissions to 2100*. MIT Joint Program for the Science and Policy of Global Change Report No. 123, Cambridge, MA.

Babiker, M., G. Metcalf, and J. Reilly. 2003a. Tax distortions and global climate policy. Journal of Economic and Environmental Management 46:269-287.

Babiker, M., L. Viguier, J. Reilly, A. D. Ellerman, and P. Criqui. 2003b. The welfare costs of hybrid carbon policies in the European Union. Environmental Modeling and Assessment 8:187-197.

Babiker, M., J. Reilly, and L. Viguier. 2004. Is emissions trading always beneficial. Energy Journal 25(2):33-56.

Felzer, B., J. Reilly, J. Melillo, D. Kicklighter, M. Sarofim, C. Wang, R. Prinn, and Q. Zhuang. 2005. Future effects of ozone on carbon sequestration and climate change policy using a global biogeochemical model. Climatic Change 73:345-373.

Hyman, R. C., J. M. Reilly, M. H. Babiker, A. De Masin, and H. D. Jacoby. 2003. Modeling non-$CO_2$ greenhouse gas abatement. Environmental Modeling and Assessment 8:175-186.

Jacoby, H. D., J. Reilly, and J. R. McFarland. 2006. Technology and technical change in the MIT EPPA model. Energy Economics 28(5-6):610-631.

Matus, K. 2005. *Health Impacts from Urban Air Pollution in China: The Burden to the Economy and the Benefits of Policy*. Master's thesis, MIT.

Matus, K., T. Yang, S. Paltsev, and J. Reilly. 2006. Economic benefits of air pollution regulation in the USA: An integrated approach. Climatic Change (in press).

McFarland, J., J. Reilly, and H. J. Herzog. 2004. Representing energy technologies in top-down economic models using bottom-up information. Energy Economics 26:685-707.

Metcalf, G., M. Babiker, and J. Reilly. 2004. A note on weak double dividends. Topics in Economic Analysis & Policy 4(1): Article 2.

Otto, V. M., A. Löschel, and J. Reilly. 2006. *Directed Technical Change and Climate Policy*. MIT Joint Program for the Science and Policy of Global Change Report No. 134, Cambridge, MA.

Paltsev, S., J. M. Reilly, H. D. Jacoby, and K. H. Tay. 2004. *The Cost of Kyoto Protocol Targets: The Case of Japan*. MIT Joint Program for the Science and Policy of Global Change Report No. 112, Cambridge, MA.

Paltsev, S., J. M. Reilly, H. D. Jacoby, R. S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker. 2005a. *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4*. MIT Joint Program for the Science and Policy of Global Change Report No. 125, Cambridge, MA.

Paltsev, S., H. Jacoby, J. Reilly, L. Viguier, and M. Babiker. 2005b. Modeling the transport sector: The role of existing fuel taxes. In: *Energy and Environment,* R. Loulou, J-P. Waaub, and G. Zaccour, eds. Springer, New York: 211-238.

Prinn, R. G. 2007. Ecosystem-climate feedbacks studied with an integrated global system model. Pp. 97-99 in *Understanding and Responding to Multiple Environmental Stresses*. Washington, D.C.: The National Academies Press.

Prinn, R., J. Reilly, M. Sarofim, C. Wang, and B. Felzer. 2006. Effects of air pollution control on climate. In: Integrated Assessment of Human-Induced Climate Change. M. Schlesinger, ed. Cambridge University Press (in press).

Reilly, J., and K. Richards. 1993. An economic interpretation of the trace gas index issue. Environmental and Resource Economics 3:41-61.

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov, and C. Wang. 1999. Multigas assessment of the Kyoto protocol. Nature 401:549-555.

Reilly, J., M. Babiker, and M. Mayer. 2001. *Comparing Greenhouse Gases.* MIT Joint Program on the Science and Policy of Global Change. Report No. 77, Cambridge, MA.

Reilly, J. M., H. D. Jacoby, and R. G. Prinn. 2003. *Multi-Gas Contributors to Global Climate Change*. Arlington, VA: Pew Center on Global Climate Change.

Reilly, J., B. Felzer, S. Paltsev, J. Melillo, R. Prinn, C. Wang, A. Sokolov, and X. Wang. 2004. The economic impact of climate, $CO_2$, and tropospheric ozone on crop yields in China, the US, and Europe. EOS Abstract 7314; B33A-0239.

Reilly, J., S. Paltsev, B. Felzer, X. Wang, D. Kicklighter, J. Melillo, R. Prinn, M. Sarofim, A. Sokolov, and C. Wang. 2006. Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone. *Energy Policy* (in press).

Sarofim, M., C. E. Forest, D. M. Reiner, and J. M. Reilly. 2005. Stabilization and global climate policy. Global and Planetary Change 47:266-272.

Schafer, A., and H. D. Jacoby. 2003. Technology detail in a multi-sector CGE model: Transport under climate policy. Energy Economics 27(1):1-24.

Sokolov, A. P., C. A. Schlosser, S. Dutkiewicz, S. Paltsev, D. W. Kicklighter, H. D. Jacoby, R. G. Prinn, C. E. Forest, J. Reilly, C. Wang, B. Felzer, M. C. Sarofim, J. Scott, P. H. Stone, J. M. Melillo, and J. Cohen. 2005. *The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation.* MIT Joint Program for the Science and Policy of Global Change Report No. 124, Cambridge, MA.

Sue Wing, I. 2003. *Induced Technical Change and the Cost of Climate Policy*. MIT Joint Program for the Science and Policy of Global Change Report No. 102. Cambridge, MA.

Yang, T., J. Reilly, and S. Paltsev. 2005. Air pollution health effects: Toward an integrated assessment. Pp. 267-293 in *Coupling Climate and Economic Dynamics*, A. Haurie and L. Viguier, eds. Berlin: Kluwer Publishers.

# CLIMATE CHANGE, MULTIPLE STRESSES, AND AGRICULTURE: WHEN ALL ELSE IS NOT EQUAL

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Scientific understanding of how agricultural systems respond to rapid social and environmental change has largely been obtained using research approaches that focus on individual stresses or forcings (e.g., air pollution, climate variability and change, pests and pathogens, loss of genetic diversity, desertification, and land degradation) most often in isolation from one another. Interactions among such stresses are poorly studied, even within integrated assessment modeling frameworks. When focusing on a single stressor, assumptions that all else is equal are the convention.

Agricultural ecosystems currently feed a population of just over 6 billion people, providing enough food for the average global citizen to consume 2,790 calories per day. One of the great human achievements of the 20th century was the steady increase in global agricultural production due to the expansion of cropped land by mechanization plus crop varietal improvements, better plant nutrition, effective pest management, and other technological advances that increased productivity. When asked to feed a growing global population, the world's farmers and their supporting institutions responded effectively. Even more remarkable was that this increase in production occurred in the face of multiple environmental and social stresses on the food system, including widespread climate variability—prolonged droughts, severe floods, and heat waves—and likely the early stages of climate change, pest and pathogen outbreaks, loss of genetic diversity in agroecosystems, desertification and land degradation, water scarcity, war, epidemics, increasing income divides between rich and poor, government mismanagement, and global population growth, to name a few. But the news is not all good as there have been notable regional failures and there are reasons for concern looking into the future. In this abstract I review recent trends and future projections of global agricultural production and then consider how multiple stresses may alter those projections. Thesholds and nonlinearities, where they are known, are identified, and research gaps and opportunities are mentioned.

One of the greatest stresses on global agriculture has been the historic rise in population and per capita income, both of which constitute the principal determinants of global food demand. Global food demand governs the scale at which the world's farmers must produce in order to maintain healthy and productive lifestyles of all people. This stress will continue into the future, although there is reason for optimism. Recent revised United Nations population projections to 2050 anticipate that the deceleration of world population growth may be even faster than previously thought. The most recent Medium Variant projection for the world population in 2050 has been revised down to 9.1 billion from its previous projection of 9.3 billion. The slowing population growth—1.6 percent p.a. today versus 0.6 percent p.a. for 2050—combined with a growing percentage of the world population reaching adequate levels of nutrition (due to increasing per capita income, especially in developing countries), leads to a gradual slowing down of growth in world demand for food and, correspondingly, in world production required to meet demand.

Recent estimates by the Food and Agriculture Organization project annual growth in world agricultural production to decline from 1.6 percent in 2000-2015 to 1.3 percent in 2015-2030 and 0.8 percent in 2030-2050 due to slowing growth in world agricultural demand. This still implies a roughly 55 percent increase in world production by 2030 compared to current production. These projections assume that in the developing countries (where almost all global land expansion takes place, mainly in sub-Saharan Africa and Latin America) another 185 million ha of arable land (+19 percent) will be brought into production between now and 2050 and another 60 million ha of irrigated land (+30 percent). Average cereal yields in the developing countries would have to rise from 2.7 tonnes/ha now to 3.8 tonnes/ha by 2050.

No clear picture of how climate change is likely to alter the above assessment has emerged in the literature. The preponderance of global agricultural studies suggest that climate change is likely to diminish global agricultural capacity by only a few percent if at all by 2050 when taking into account regions that may benefit (i.e., North America, Europe) and regions that may suffer (i.e., the tropics). Any losses would be on top of substantial gains in world output as noted above. A small suite of modeling studies predict that world crop (real) prices are likely to continue to decline through the first two to three degrees C of warming before rising with additional warming (IPCC TAR, 2001/5)—*hence, two to three degrees of warming appears to be a crucial threshold for crop prices*.

While the global situation looks manageable, there are several reasons for concern at regional levels. Several stresses on agricultural production systems are impeding the achievement of regional food security, especially in the developing world. Sub-Saharan Africa is a case in point that is worth a closer look. It is a region in which stresses on food security occur across several levels of scale. Table 1 lists some examples of major stresses on sub-Saharan Africa that operate at global and regional/local levels.

Agricultural stressors in sub-Saharan Africa operating at the global scale include *climate change* and *widening agricultural trade deficits*. Tropical cropping systems have been shown to be vulnerable to even the slightest increase in temperatures because, for most of the major food crops being grown there, mean maximum temperatures are already at the high end of effective photosynthetic temperatures. Modeling studies project tropical crop yields (rice, maize) to fall markedly with only a one degree warming, even when $CO_2$ fertilization is considered—*such is a critical threshold*. In addition, most of the nations of sub-Saharan Africa became net food importers in the early 1980s and are expected to see their

**TABLE 1** Stressors on Sub-Saharan Africa Food Security

Global
- Climate change
- Widening agricultural trade deficits

Local and Regional
- Rapid population growth
- Emerging infectious diseases, i.e., HIV/AIDS
- Lack of safe drinking water, public health
- Rising incomes leading to dietary changes, i.e., more meat consumption
- Political instability and civil strife
- Long-term drought
- Land degradation

agricultural trade deficit quadruple by 2030. This has inhibited the development of the agriculture sector in the region and limited agricultural income growth, which is a major driver of development.

Agricultural stressors in sub-Saharan Africa operating at regional to local scales include a number of social and environmental challenges. Food production across most of Africa has not kept up with *rapid population growth*. The population of sub-Saharan Africa is currently growing at a rate of 2.6 percent p.a. and is expected to grow at 2.2-2.6 percent p.a. out to 2030, which is more than double the world average. Sub-Saharan Africa is the only region of the world where per capita food consumption not only remained below acceptable levels (less than 2200 Kcal/day), but has fallen in the last two decades. The effect of *emerging infectious diseases* such as HIV/AIDS on population growth will be minimal, but their effect on agricultural productivity could be catastrophic. The U.S. Census Bureau estimates that over 40 percent of the reproductive-age population in South Africa is HIV-positive. FAO projects that 20 percent of South Africa's agricultural labor force will have been lost to HIV/AIDS over the period 1985-2020. This epidemic strikes a population that has generally *poor levels of public health* and *inadequate access to safe drinking water*, which are stresses by themselves. On top of these demographic and public health stresses, sub-Saharan Africa experiences widespread *political instability and civil strife* that has particularly interrupted the distribution of food to people who need it most.

Several environmental problems will continue to stress the sub-Saharan food production system. Southern Africa experienced *protracted droughts* throughout the 1990s and is considered to be in a dry period relative to the longer-term historical record. Again, no clear picture has emerged as to how the frequency and intensity of droughts may be changed by climate change across sub-Saharan Africa. The *degradation of land resources* by agriculture becomes a major feedback limiting future agricultural productivity due to deterioration of the land resource base. This is problematic throughout sub-Saharan Africa. Processes at work include salinization of irrigated areas, overextraction of groundwater, chemical depletion of soils, water saturation, leaching of nitrate into water bodies (pollution, eutrophication), off-site deposition of soil erosion sediment, and enhanced risks of flooding following conversions of wetlands to cropping. There is a great deal of debate over how much land degradation has affected crop productivity. Some estimates suggest that land degradation has reduced crop productivity by 25 percent in Africa since World War II.

How the many stresses listed above fit together in determining the vulnerability and resiliency of sub-Saharan agriculture is not known with any certainty. The same can be said virtually anywhere else in the world. Environmental stressors surely interact strongly with social and economic stressors. A drought may substantially reduce crop yields, but temporary crop price increases brought on by production disruptions may offset the stress to farmers, although the consumer pays more. Major gaps exist in understanding how multiple stresses on agriculture and food security interact. The following list details some potential priorities that might help address these gaps:

- Compilation of datasets on agriculture and food-related stresses using GIS technology—data should be scalable and easily assembled in different geographic units and time scales
- Improvement in basic understanding of how multiple stresses interact to influence important quantities, such as crop yields, public health, regional and per capita income, and the like—special attention should be paid to identifying nonlinearities and thresholds
- Development of modeling methodologies in which interactions between multiple stressors (social and environmental) are explicit
- Design and implementation of comprehensive food system monitoring capabilities leveraging the success of the U.S. Agency for International Development's Famine Early Warning System
- Improvement in basic understanding of the resiliency of agricultural systems in the face of not one but several stresses occurring simultaneously, especially the identification of system redundancies and other coping strategies

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# SOCIOECONOMIC IMPACTS OF MULTIPLE STRESSES ON CITIES

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Four issues require attention when analyzing the socioeconomic impacts of multiple stresses on cities when reflecting on possible adaptive strategies: (1) weight of path dependency, (2) importance of scale, (3) usefulness of existing analytic tools, and (4) role of institutions. All will be described in terms of what has been learned, which research gaps still exist, and how understanding multiple stresses might affect the conduct of future research, assessments, and decision making.

## DEVELOPMENT PATHWAYS: KEY LINK BETWEEN MULTIPLE STRESSES AND DRIVERS?

Many of the forces behind emissions trajectories and land use changes induced by urban areas, such as economic growth, technological transformations, demographic shifts, and governance structures, are similar or even the same to those underlying diverse pathways of development, explaining in part why

1. industrialized countries and the wealthy in the South account for the highest share of atmospheric emissions, and have much higher ecological footprints (e.g., land use changes induced by cities' demands on wood) than poor countries, regions, and sectors. Rees and Wackernagel (1996) have documented the influences and effects of world cities, such as Amsterdam in distant places ("teleconnections"). Another example is the demand for meat in Mexico City, which led in the 1950s and 1960s to land cover changes in Tabasco 400 km away (Barkin et al., 1978).
2. some regions and sectors, especially from the developing world, are more vulnerable to impacts such as climate variability and change than others. The poor in urban areas for example lack access to climate-controlled shelters; they already face environmental problems (sanitation, deficiencies in the operation of public services, location in risk-prone areas); they suffer malnutrition, poor housing conditions, and low income. All those conditions that have been further worsened by structural adjustment programs implemented during the last two decades may produce a highly segregated urban space and contribute to aggravate—especially for the poor—the negative impacts of changes in biophysical processes in urban areas.

If the impacts of changes in atmospheric composition go beyond a certain threshold and/or urban areas are not prepared to deal with that level of impact, then cities from both the developed and the developing world may become vulnerable. Consider the 2003 heat wave in Europe as example of an event a developed country like France was vulnerable to. This did not necessarily result from lack of resources. But it rather related not only to health conditions and health services for the elderly people, but also to social conditions and organization (i.e., to inadequate climate conditioning in buildings; to the fact that the elderly people were alone while their families were on vacation). Think about environmental change's possible impacts on the pool of resources and ecosystems an urban area relies on. As some scenarios foresee, climate change will strongly affect already stressed watersheds in both the developing world (e.g., Lerma and Cutzamala for Mexico City) and the developed world (Colorado River for Southern California).

The problem is that most scholars tend to focus either on some drivers of emissions trajectories (e.g., IPCC's Work Group III) or on the vulnerability or impact to multiple stresses (e.g., IPCC's Work Group II using vulnerability assessments). And knowledge would advance faster if both groups could explore and model the complex linkages between drivers of development pathways and stressors facing urban sectors and localities. Consider another example. Market forces and the declining role of the state as urban planner are key drivers of urban growth in risk-prone areas of developing countries and even of industrialized countries—as New Orleans has recently shown us. The retrenchment of the state in its role as regulator usually appears as one of the multiple stresses facing urban dwellers. Wouldn't it be better to explore how market forces and other drivers relate or cascade with other and multiple stresses to produce certain vulnerabilities/adaptive capacities? Isn't it a challenge to develop an integrated perspective to understand the pathways through which socioeconomic, institutional, and environmental processes influence livelihoods, economic activities, urban life, migration, and other realms where adaptive capacity takes place in urban areas?

## RELEVANCE OF SCALE

Scale is important in diverse and not yet fully explored ways when assessing the socioeconomic impacts of changes in atmospheric composition and dynamics.

- First, the referred changes are but a part of a set of multiple stresses operating at diverse scales in space and through time (e.g., markets, deficiencies in housing, or in the supply and operation of urban services, infrastructure, sanitation, and health). The problem is that research on this issue is in its infancy. We need to better understand—and if possible model—the global and regional socioeconomic, geopolitical, and environmental processes affecting the vulnerability of urban systems.

- Second, both the exposure to and the distribution of urban groups and localities sensitive to the impacts of changes in atmospheric composition and dynamics vary greatly across scale. The primary social and economic conditions that influence adaptive capacity (e.g., access to financial resources or to governmental relief) also differ with scale. One could say, for instance, that at a national scale cities in industrialized countries such as Norway or the United States can cope with most kinds of gradual environmental changes, but focusing on more localized differences (between New York and New Orleans for instance) can show considerable variability in stresses and capacities to adapt. This is another area where more research is needed.
- Third, temporal scale is a critical determinant of the capacity of urban systems to adapt to environmental changes. The history of the city—path dependency—will determine the diversity and complexity of its population's current and future adaptive capacity. Of course, rapid changes or abrupt changes (e.g., flooding, droughts) are more difficult to absorb without painful costs than gradual change. But gradual change can accumulate until urban areas reach a threshold in which their adaptive capacity is no longer feasible. Consider how slow changes in the length and frequency of seasons could affect water supplies in cities, or how slow changes in temperature and humidity could affect the livelihood of urban people. These issues have received little attention so far.

## ANALYTICAL TOOLS

Rather than using one-dimensional perspectives to understand the responses of urban areas to the impacts of changes in the composition of the atmosphere, we need broader multidimensional and multiscale approaches. This is a challenge indeed. Examples of such tools and concepts that will be described in this section are the Kaya identity, vulnerability/adaptation assessments, livelihoods, and tolerable windows approach. According to the IPAT identity, environmental impact is the product of the level of population combined with affluence (e.g., measured by income per capita) and the level of technology (e.g., measured by emissions per unit of income). Numerous articles use this kind of identity to analyze the drivers of $CO_2$ emissions (Kaneko and Matsouka, 2003), often referring to it as the "Kaya identity," according to which:[2]

$$CO_2 Emissions = Population \cdot \left(\frac{GDP}{Population}\right) \cdot \left(\frac{Energy}{GDP}\right) \cdot \left(\frac{CO_2}{Energy}\right)$$

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[2] Note that some of the components can be analyzed for sectors of activity to get greater detail of emissions sources.

The Kaya identity has the advantage of being simple and allowing for "some standardization in the comparison" and analysis of diverse emissions trajectories (Nakicenovic, 2004). Clearly, it is a very general way of looking at emissions; for example, it assumes that each variable enters linearly and independently, which is surely not the case, and it omits other factors (such as institutional ones) as emissions drivers that are left as residual of the equation if looking at past emissions evolution (IPCC, 2000; Nakicenovic, 2004). The identity is broadly used to construct scenarios; it helps to identify proximate but not ultimate drivers, but it fails to identify many key drivers—e.g., government regulation, social organization, and economic organization, as well as public perceptions, which influence patterns of technologies in use affecting trajectories of greenhouse gases and other atmospheric releases.[3] The question is whether a similar equation in which the variables do not enter independently could be applied to the analysis of multiple stresses, whether such an equation could at least allow for some standardization in the comparison of diverse cases.

Rather than selecting a particular environmental stress of concern and trying to identify its consequences as impact assessment does, vulnerability/adaptation assessments:

1. Choose a group or unit of concern (e.g., informal or wealthy settlements, poor or rich urban dwellers).
2. Try to evaluate the risk of specific adverse outcomes for that unit when confronted with a set of stresses (e.g., climate variability and change, new patterns of foreign direct investment and of industrial location, and structural adjustment programs). Note that all these stresses redefine the economic base of urban areas, drive new territorial patterns of urban growth and new emissions trajectories (Romero Lankao et al., 2005); at the same time they define a new physiognomy and geography of vulnerable groups and localities within the cities.
3. Seek to identify a set of factors (e.g., institutions, assets, social capital) that may reduce or to the contrary enhance adaptation to those stressors.

Precisely because vulnerability assessments concentrate on exposure units, they assume that vulnerability is highly dependent on scale and context. This has two consequences we should address in our workshop. Assessments focusing on a narrow range of scales will miss most of the importance for societal efforts to cope with the impacts of changes in the atmosphere. It is therefore essential for

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[3] One such case is two institutional changes—privatization of state firms and decreased public expenditures—happening during the 1990s in Mexico City. They were aimed at eliminating inefficient and insolvent enterprises, thereby reducing public expenditure. Those transformations became one of the drivers of the shift in mode share from Metro and buses to minibuses and low-capacity modes, by this in increasing GHG emissions by the transportation sector (Romero Lankao et al., 2005).

vulnerability assessments to address multiple drivers and stresses that interact across a variety of scales.

One tool is under development within the IPCC community and intends to deal with the future: the tolerable windows approach. This tool selects an exposure unit and classifies the potential outcomes either as acceptable or adverse. The next step is to try to define the dynamic combination of environmental and socioeconomic and institutional stresses that could result in negative outcomes. For this it is necessary to develop scenarios of the future that include not only environmental stresses but also socioeconomic stresses (Toth, 2001).

Livelihood analysis is another multidimensional concept applied to both rural and urban studies. It pays attention to the way in which a living is obtained and gives especial consideration to agency. Livelihood analysis comprises "the capabilities, assets (stores, resources, claims, and access) and activities required for a means of living" (Ellis, 2000). The tool is useful to study how individuals, households, and communities in cities adapt to the impacts of changes in the composition of the atmosphere. It pays attention to the social, economic, institutional, and environmental dimensions of adaptation strategies by those agents; it explores how those dimensions interact at different scales. This tool can offer insights to design policies aimed at both enhancing adaptation to the impacts of atmospheric changes and reshaping the socioeconomic impacts of existing urban development pathways.

I would like to close this paper with one citation and some thoughts on the role of institutions in adapting to the impacts of changes in the composition of the atmosphere. According to Steffen et al. (2003):

> The current states of vulnerability research and vulnerability assessment exhibit both the potential for substantial synergy in addressing global environmental risks . . . as well as significant weaknesses which undermine that potential. A substantial base of fundamental knowledge has been created. However it is highly fragmentary in nature, with competing paradigms, conflicting theory, empirical results often idiosyncratic and tied to particular approaches, and a lack of comparative analysis and findings.

My guess is that one research path for us is to develop meta-analytic tools to tease out the paradigms behind those approaches and to see whether and, if so, at which levels it is possible to make those analyses and their findings comparable.

## INSTITUTIONS

Last but not least, institutions play a significant role both as drivers/stressors (IDGEC, 2005; Romero Lankao et al., 2005) and as enhancers of urban systems' ability to cope with and adapt to the negative impacts of changes in atmospheric composition and land use (IDGEC, 2005). As already mentioned in this paper the first task we are confronted with is to understand within an integrated perspective the pathways through which institutions together with other socioeconomic and environmental processes influence livelihoods, economic activities, urban life, migration, and other realms where adaptive capacity takes place in cities. The second and more difficult task is to consider existing research on the science policy interface, which may help us understand

1. why and how decision makers relate to scientific information and findings on socioeconomic and institutional impacts of changes in land use and in atmospheric composition;
2. the resources and institutional capacity decision makers have to design and implement adaptation strategies;
3. the role of other organizations, institutions, and stakeholders in the design and implementation of adaptation strategies.

## REFERENCES

Barkin, D., con la colaboración de Adriana Zavala. 1978. *Desarrollo regional y reorganización Campesina: La Chontalpa como reflejo del problema agropecuraio mexicano*. Mexico: Editorial Nueva Imagen.

Bruchner, T., G. Petschel-Held, F. L. Tóth, H.-M. Füssel, C. Helm, M. Leimbach, and H.-J. Schellnguber. 1999. Climate change decision-support and the tolerable windows approach. Environmental Modeling and Assessment 4:217-234.

Ellis, F. 2000. *Rural Livelihood and Diversity in Developing Countries*. Oxford: Oxford University Press.

Kaneko T., and Y. Matsouka. 2003. Driving forces behind the stagnancy of China's energy related $CO_2$ emissions from 1996-1999: The relative importance of structural change, intensity change and scale change. Draft.

Nakicenovic, N. 2004. Socioeconomic driving forces of emission scenarios. Pp. 225-239 in *The Global Carbon Cycle: Integrating Humans, Climate and the Natural World,* C. B. Field and M. R. Raupach, eds. Washington, D.C.: Island Press.

Rees, W., and M. Wackernagel. 1996. Urban ecological footprints: Why cities can not be sustainable—and why they are a key to sustainability. Environmental Impact Assessment Review 16:223-248.

Romero Lankao, P., H. López Villafranco, A. Rosas Huerta, G. Günther, and Z. Correa Armenta, eds. 2005. *Can Cities Reduce Global Warming? Urban Development and the Carbon Cycle in Latin America.* México, IAI, UAM-X, IHDP, GCP. 92 pp.

Steffen, W., A. Sanderson, P. D. Tyson, J. Jäger, P. A. Matson, B. Moore III, F. Oldfield, K. Richardson, J. Schellnhuber, B. L. Turner II, and R. J. Wasson. 2004. *Global Change and the Earth System: A Planet Under Pressure.* Berlin, Heidelberg, New York: Springer-Verlag.

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# UNDERSTANDING VULNERABILITY OF ECOSYSTEM GOODS AND SERVICES AND RESPONSE STRATEGIES

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*Questions suggested*: (1) What has been the economic impact of large-scale stresses to ecosystems, and how has this impact been characterized? (2) How is vulnerability of ecosystem goods and services characterized? (3) How best can society value ecosystems and ecosystem goods and services to effectively prepare for the impact of multiple stresses?

## BROAD RESPONSE

It is important to approach these questions from a dynamic systems perspective within which environmental and socioeconomic systems are interacting over time, each affecting the other. Economic impacts are not simply "there" to be identified by the economist but rather are a product of prior conditions. Thus the economic impact of large-scale or multiple stresses is very dependent on how well we are prepared for and how well we respond to the stresses. Hurricane Katrina laid bare the human and economic costs of being ill prepared and unresponsive. The critical point here is that a particular stress, or particular combination of stresses, does not map to a particular economic impact. Between a stress and an impact there are typically human-modified environments, technological systems, and socioeconomic institutions and capabilities whose states and hence responses to stresses depend on both preceding stresses and human decisions to recognize, develop, and protect environmental qualities, technological capacities, and institutional capabilities.

Thus the economic implications of an extended drought in the Midwest that seriously jeopardized corn, soybean, and wheat production depends on the existence, or not, of the agroecological, technological, and socioeconomic conditions necessary to raise alternative grains that are quite normally grown, for example, in arid regions of India. The definition of a drought (i.e., is there enough water?) is not simply a matter of the difference between rainfall and crop needs, or between soil storage, rainfall, and evapotransporation. Need, evapotransporation, and soil storage depend on the crops grown.

As we saw in the case of Katrina, the distribution of income can also critically affect the impacts observed. The human toll of an extended drought in the Midwest could be no more than the discomfort of foregoing beef and eating soy burgers. During the stress of World War II, margarine became a normal food in the American diet through programs that restricted the availability of butter for all. But if the rich continue to eat beef through a drought, the price of grains could quickly become a major hardship on the poor.

Similarly, there are scalar issues associated with risk that are critical. Historically, near-subsistence farmers planted a variety of crops in the expectation that some of them would fit the weather conditions of a particular year. With trade and specialization, risks and risk reduction strategies become distributed more globally. Thus, low corn, soybean, and wheat yields in the United States in any particular year or decade are dampened by global production unless, as is possible with climate change, much of the globe is affected in the same period. A rapid transition in climate conditions could also occur globally such that globalizing risk becomes a less effective strategy.

We should be as concerned about combinations of social and environmental stresses as about combinations of environmental stresses. It was much more difficult to be prepared for and to respond to the combination of stresses known as the "dust bowl" during the Great Depression because the social system was already highly stressed by a dysfunctional economy. No doubt environmental stresses during World Wars I and II also resulted in greater hardship because social system resources were devoted to the wars. It is also important to keep in mind that the social conditions, specifically the movement of soldiers and material at the end of World War I, helped spread the Spanish Flu virus, which ended up killing 10 times as many Americans as the Great War.

We have a tendency to think of fair to good socioeconomic times as normal and bad as the exception, but surely 20 percent of the years in the United States during the 20th century were pretty bad. And just as surely, 20 percent of the world's population at any one time is engaged in a civil or regional war or having bad economic times. Yet most of our scenarios for "sustainable development" are built around fair to good times being an uninterrupted norm.

Acknowledging the dynamic interactions between social and environmental systems has not yet led to the incorporation of appropriate models to address periodic stresses in environmental assessments, let alone combinations of stresses. Efforts to date to portray the interactions between social systems and environmental systems in assessments tend to forecast alternative smooth scenarios. For example, the assessments by the Intergovernmental Panel on Climate Change are tied to alternative scenarios that differ, for example, by overall rates of growth, types of technology, and differences between industrialized and less industrialized countries, but these scenarios play out without discontinuities. The scenarios of the Millennium Ecosystem Assessment are more heuristic and the differences between them with respect to resilience overall, patchiness globally, and protection of the poor to stresses are discussed but not actually quantified.

Valuation of ecosystem services as a technique has also presumed a steady forecast of good times, both environmentally and socially (at least for the rich). Because a dollar of a poor person tends to be counted the same as the dollar of a rich person, ecotourism values, for example, can swamp subsistence ecosystem services important to the poor. Clearly it is these more basic values that are more important to be studying now that we are more concerned about multiple stresses.

In any case, we value what we know, and as the uncertainty of the future becomes more clear to more people, we will value ecosystem services differently. This is rather a circular problem, for we want the values to inform people of the importance of ecosystem services. But to the extent that some of the ways economists derive values flow from an informed public expressing choices, most ecosystem services, especially under conditions of stress, are highly undervalued because people are less aware of the importance of the services than they should be.

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# PATTERNS, SOURCES, AND IMPACTS OF DECADAL-TO-MULTIDECADAL CLIMATE VARIABILITY IN THE WEST

*Julio L. Betancourt*[4]
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Both instrumental and tree-ring records show that the western U.S. climate exhibits low-frequency modes in the form of persistent and widespread droughts that alternate with pluvials. Some notable examples are the dry Medieval period (A.D. 900-1300) and the ensuing wetter Little Ice Age (A.D. 1400-1850); the dramatic switch from the megadrought in the late 1500s to the megapluvial in the early 1600s; and the bracketing of epic droughts in the 1930s and 1950s by two of the wettest periods (1905-1920 and 1965-1995) in the last millennium. Such decadal-to-multidecadal (D2M) hydroclimatic variability is assumed to operate through the oceans and clearly can occur independent from anthropogenic forcing. Statistical and modeling studies show teleconnections to low-frequency SST variability in the Pacific, Indian, and North Atlantic Oceans, and there is mounting interest in both mechanisms and predictability.

D2M precipitation variability in the western United States tends to be spatially coherent and can synchronize physical and biological processes in ways that are complex and difficult to forecast and monitor. D2M variability can synchronize fluctuations in surface water availability across major basins and can thus overextend regional drought relief and interbasin transfer agreements. Traditionally, both water resource and floodplain management in the West have been based mostly on stationary assumptions about surface flow—that the mean and moments of the annual or peak discharge distributions do not change over time. Federal flood insurance relies on the concept of the 100-year flood, which is calculated routinely with flood frequency methods that assume stationarity. And we also assume stationarity in annual operations of critical water resources. For instance, Article III of the Compact apportions 7.5 million acre feet (MAF) per year each to the Upper and Lower Colorado River Basins, stipulates that Upper Basin states cannot deplete the flow at Lees Ferry by more than 75 MAF over a period of 10 consecutive years and mandates a moving 10-year average release of 8.23 MAF/year from Lake Powell into the Lower Basin. In the case of D2M variability, 100 years may not be long enough to evaluate stationary assumptions in water resource planning, and we are forced to rely on tree-ring reconstructions of precipitation and streamflow. These reconstructions vary in coverage and quality, but nonetheless are a good first approximation of the history and long-term probability of D2M precipitation and streamflow regimes. In particular, probability distribution functions from long reconstructions of hydroclimate (precipitation or

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[4] Dr. Betancourt was unable to attend the workshop; his slides and perspectives were integrated into Jonathan Overpeck's presentation.

streamflow) or climatic index series (AMO, PDO, etc.) can be used to calculate the occurrence and return probabilities of climatic episodes. This information can then be mapped to decisions about annual water resource operations or facilities planning.

By synchronizing ecological disturbances and recruitment pulses, D2M variability also plays a key role in structuring woodland and forest communities in western watersheds. In the event of longer, hotter growing seasons, D2M variability will still determine the timing and pace of ecosystem changes. Oscillations between warm-dry and warm-wet regimes will continue to produce uncommonly large disturbances followed by accelerated regeneration and succession. Such large-scale vegetation changes will have complex hydrological effects and will add further uncertainty to water resource availability. A principal challenge for land managers in the 21st century will be to manage for disturbance and succession in purposeful and systematic ways that promote asynchrony and patchiness at local to regional scales while still preserving goods and services that ecosystems provide.

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# APPENDIX E

# Committee Biosketches

**ROSINA M. BIERBAUM** (*Co-chair*) is dean of the University of Michigan's School of Natural Resources and Environment and professor of natural resources and environmental policy. Prior to her appointment at Michigan, she served as acting director of the Office of Science and Technology Policy (OSTP) in the Executive Office of the President. She joined OSTP in November 1993 as a senior policy analyst and served as assistant director for environment before being confirmed by the U.S. Senate as associate director. As the Administration's senior scientific advisor on environmental research and development, Dr. Bierbaum provided scientific input and guidance on a wide range of national and international environmental issues, including global change, air and water quality, endangered species, biodiversity, ecosystem management, endocrine disruptors, environmental monitoring, natural hazards, and energy research and development. Dr. Bierbaum is a fellow of the American Association for the Advancement of Science and a member of the NRC's Board on Atmospheric Sciences and Climate. She is a past member of the Government-University-Industry Research Roundtable of the National Academy of Sciences. Dr. Bierbaum received her Ph.D. in ecology and evolution from the State University of New York at Stony Brook.

**MARY ANNE CARROLL** (*Co-chair*) is director of the Program for Research on Oxidants: PHotochemistry, Emissions and Transport (PROPHET), executive director of the Biosphere-Atmosphere Research and Training Program (BART), and a professor of atmospheric, oceanic, and space sciences and chemistry and geological sciences at the University of Michigan. Her areas of interest include oxidant photochemistry, distribution, and trends; atmosphere-forest exchange of reactive nitrogen (a factor in carbon storage); and the impacts of air pollutants on ecosystem function and emissions. She served as editor for the *Journal of Geophysical Research-Atmospheres* from 1997 to 2000, is a past member of the NRC's Committee on Geophysical and Environmental Data and the Committee on Atmospheric Chemistry, and a current member of its Board on Atmospheric Sciences and Climate. Dr. Carroll received her Sc.D. in atmospheric chemistry from the Massachusetts Institute of Technology.

**Christopher B. Field** is director of the Department of Global Ecology at the Carnegie Institution of Washington and professor by courtesy in the Department of Biological Sciences at Stanford University. Trained as an ecologist, Dr. Field has conducted environmental research from tropical rainforests to deserts to alpine tundra. He developed an evolutionary approach to understanding the spatial organization of plant canopies and the adaptive significance of leaf aging. These studies led to work on the role of nitrogen in regulating plant growth and photosynthesis and suggested ways that plant physiological responses could be summarized with a few parameters, providing a basis for predicting many aspects of ecosystem function at very large scales. He has recently emphasized formalizing approaches for summarizing plant responses into models that simulate ecosystem exchanges of carbon, water, and energy at the global scale. These models help test hypotheses and understand the future status of terrestrial ecosystems, especially responses to and influences on global change factors like increased atmospheric carbon dioxide or altered climate. Dr. Field is a member of the National Academy of Sciences and the NRC's Board on Environmental Studies and Toxicology. He received his Ph.D. in biology from Stanford University.

**Edward L. Miles** is the Virginia and Prentice Bloedel Professor of Marine and Public Affairs in the School of Marine Affairs at the University of Washington and senior fellow at the Joint Institute for the Study of Atmosphere and Oceans. Since 1965 Dr. Miles has worked at the interface of the natural and social sciences and law with a focus on outer space, the oceans, and the global and regional climate systems. Trained originally in political science and international relations, he has invested close to 30 years in learning about oceanography and fisheries science/management and 13 years in learning about the planetary climate system. His research and teaching interests have encompassed international science and technology policy; the design, creation, and management of international environmental regimes; a wide variety of problems in national and international ocean policy; and the impacts of climate variability and climate change at global and regional space scales. Dr. Miles is a member of the National Academy of Sciences and the NRC's Committee on the Human Dimensions of Global Change and Policy and Global Affairs Committee. He received his Ph.D. in international relations/comparative politics from the University of Denver.

**Donald A. Wilhite** is founder and director of the National Drought Mitigation Center and International Drought Information Center and a professor in the School of Natural Resources at the University of Nebraska-Lincoln, where he has been on the faculty since 1977. His areas of interest include drought preparedness, mitigation and policy, climate and drought monitoring, the policy implications of climate variability and climate change, and the effects of climate on society. In conjunction with this research, he has worked with many developed and developing countries, regional organizations, and United Nations agencies on drought management and policy issues. He has also conducted numerous training seminars and workshops on drought planning and management. Dr. Wilhite is chair of the drought discussion group for the U.N.'s Secretariat for the International Strategy for Disaster Reduction. He received his Ph.D. in geography, climatology, and water resources from the University of Nebraska.