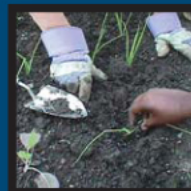
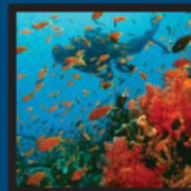


# Complex Environmental Systems

Pathways to the Future



NSF Advisory Committee for  
Environmental Research and Education



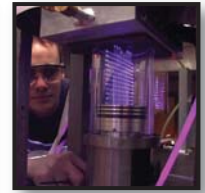
## About the Advisory Committee for Environmental Research and Education

In 2000, the National Science Foundation (NSF) established the Advisory Committee for Environmental Research and Education (AC-ERE) under the Federal Advisory Committee Act (FACA) to:

- Provide advice, recommendations, and oversight concerning support for NSF's environmental research and education portfolio.
- Be a base of contact with the scientific community to inform NSF of the impact of its research support and NSF-wide policies on the scientific community.
- Serve as a forum for consideration of interdisciplinary environmental topics as well as environmental activities in a wide range of disciplines.
- Provide broad input into long-range plans and partnership opportunities.
- Perform oversight of program management, overall program balance, and other aspects of program performance for environmental research and education activities.

The AC-ERE has a particular interest in those aspects of environmental science, engineering, and education that affect multiple disciplines. Each of the directorates and major offices of NSF has an advisory committee that provides guidance on the disciplinary activities within that directorate. The AC-ERE includes scientists and engineers from many disciplines, including a member from each of the other NSF advisory committees, and focuses on coordination, integration, and management of environmental programs across the Foundation. AC-ERE interests include environmental education, digital libraries, and cyberinfrastructure, as well as interdisciplinary programs, centers, and major instrumentation.

# Pathways to the Future

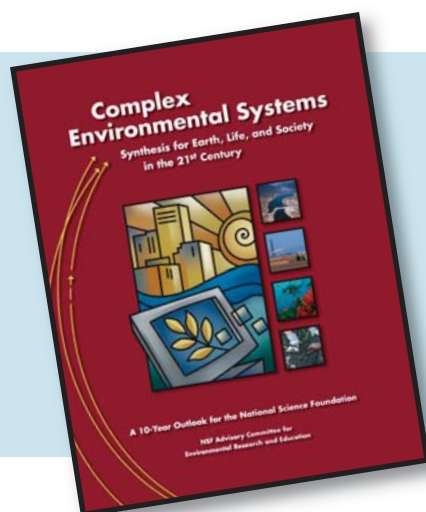


In this document, the National Science Foundation (NSF) Advisory Committee for Environmental Research and Education (AC-ERE) highlights, within the complex environmental system (CES) framework described in its previous report, timely pathways for enhancing environmental research and education (ERE) across NSF. In particular, the AC-ERE encourages NSF to maintain a Foundation-wide emphasis on investigations of coupled human and natural systems. NSF is also in a position to stimulate (1) development of new technologies and environmental cyberinfrastructure for observing, modeling, assessment, and remediation, (2) integration of molecular- to global-scale research, and ways of making these integrated results relevant to the public, (3) interdisciplinary research focused on water, (4) development of a diverse workforce of scientists and engineers who participate in environmental decision-making, and (5) increased use of scientific data and information to better inform decision-making and support society in direct and tangible ways.

Upon entering the 21<sup>st</sup> century, we face significant scientific and engineering challenges and opportunities resulting from accelerating environmental changes. New links between basic and applied research endeavors must be created, reaching

across traditional disciplinary boundaries to study CES *in toto*. Consider, for example, how difficult it is to understand and predict the role of water in the environment. Water is part of a complex system in which interactions between natural and human-designed components are dynamic, complex, and interconnected. Yet seeking understanding is critical because water not only supports life, but shapes the landscape, drives global climate systems, and influences where and how people live. New scientific and engineering research and innovation are needed to understand the changes and impact of multiple stresses on environmental systems as well as to inform responses to natural hazards. Now more than ever, scientists and engineers must address combinations of factors, such as the interactions between human activities and natural cycles at different spatial and temporal scales.

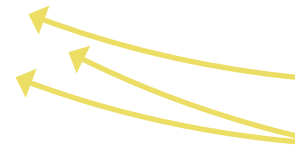
CES research has been transformative in terms of practice and outcomes. The AC-ERE urges the research community to keep on this path of change—to continue facing the challenges inherent in investigating environmental processes and to continue developing the ability to turn observations into the predictive models needed by decision-makers. This document reaffirms the AC-ERE's commitment to unraveling the complexity of environmental systems.



Over the last three years, NSF has been making great strides catalyzing interdisciplinary research in ways that have transformed the science and engineering community, as well as academe. The community has been crying out for more mechanisms to support research and education focused on today's pressing scientific problems, many of which are related to complex environmental systems. In 2003, the NSF AC-ERE published the report, *Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21<sup>st</sup> Century*, which sets out a broad framework for environmental research and education. The CES report emphasizes high-priority, interdisciplinary activities that cut across NSF's disciplinary organizational structure, and provides strategic guidance to the Foundation on its ERE activities.

# Coupled Natural and Human Systems

## As a Framework for Integrated Research in Complex Environmental Systems



Through the Biocomplexity in the Environment (BE) priority area, NSF has been instrumental in encouraging changes regarding research on complex environmental systems. BE successfully promoted new approaches to investigating the interactions between the living and non-living environment and between human and natural systems. The BE priority area, which accounted for only four percent of NSF's broad investments in ERE, showed that well-directed funding can have a disproportionately large impact. The BE competition fostered new areas of integrated research by providing collaborative, interdisciplinary teams with a mechanism for tackling complex environmental questions, including the role of humans in the environment. Additionally, BE improved public understanding through education by linking research results to the public interest. Because of BE, institutional perceptions and the practice of environmental science and engineering have changed. Many academic organizations restructured their programs to more effectively support interdisciplinary research. Additionally, journals, such as *Ecological Complexity*, were established to publish BE-type research, while other highly regarded journals dedicated special issues to BE-related topics.

The AC-ERE believes it is essential that NSF sustain the momentum created by BE and continue to foster interdisciplinary understanding of complex systems. The AC-ERE will continue to oversee and promote support of integrated research as many components of BE are folded into new and existing NSF programs.

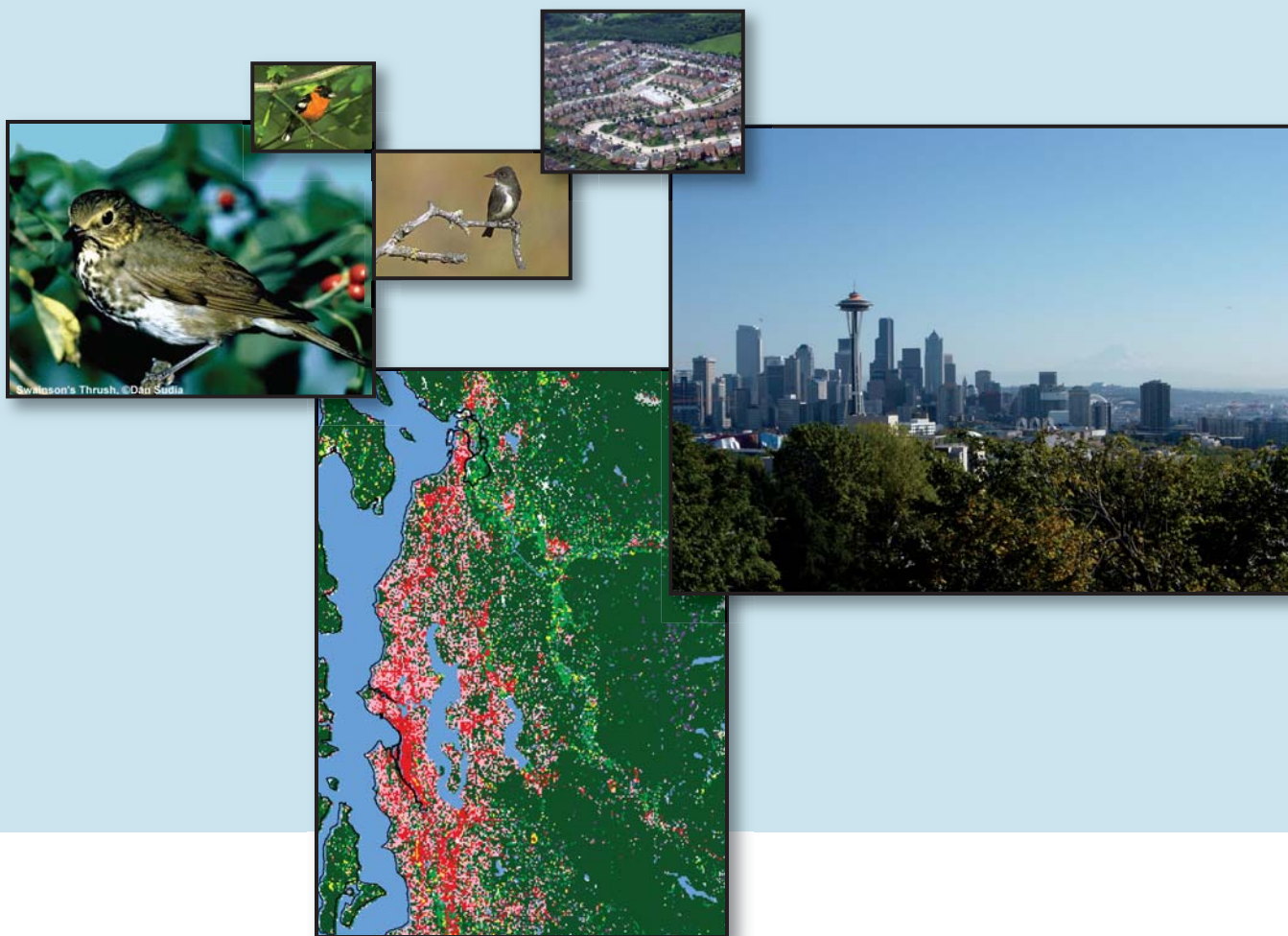
One BE theme, Dynamics of Coupled Natural and Human Systems (CNH), continues to need NSF attention and nurturing. Because it directly relates human activity with the natural environment, CNH epitomizes the high degree of complexity and integration that is central to CES. The outcomes of CNH are some of the most exciting, challenging, and potentially transformative accomplishments of BE. CNH, along with other BE research areas, supports large-scale interdisciplinary projects, explicitly requires teams that include natural and social scientists, and encourages the involvement of engineers and educators. Focusing the attention of scientists and engineers beyond a single system has enabled exploration of the ways that disparate systems interact with each other and has spurred new research approaches and dramatic breakthroughs in understanding.

The AC-ERE is particularly interested in the future of CNH. Because its programs cover the full range of natural, social, behavioral, economic, and physical sciences and engineering, NSF is uniquely positioned to advance CNH research. A challenge is reconciling different perspectives for evaluating system dynamics, bridging, for example, the experimental approaches often used when studying natural systems and the qualitative and quantitative methods often used in social science analysis. To ensure continued progress towards understanding the complex links and feedbacks between human and natural systems, CNH research is a critical component of environmental science and engineering.

## Modeling Interactions Among Urban Development, Land-Cover Change, and Bird Diversity

Building new roads and housing developments impacts ecosystem structures and functions through the conversion of land, fragmentation of natural habitat, disruption of hydrological systems, and modification of energy flow and nutrient cycles. Researchers who study urban development have very different emphases, scale, methodology, and objectives from ecological scientists, thus simulation models for the two areas have evolved in separate knowledge domains. By building on model traditions in urban economics, landscape ecology, wildlife population dynamics, and complex system science, each of which offers different perspectives on modeling urban ecological interactions, scientists at

the University of Washington have developed a framework to simulate dynamic interactions between urban development and ecological processes. The result is a new and deeper understanding of urban growth and its impacts on bird habitat than previously possible using simulations from a single research field. Such assessments of ecological impacts of urban growth that are timely, accurate, and transparent are crucial to making sound policy and management decisions. Figures courtesy of Marina Alberti, Paul Waddell, John M. Marzluff, and Mark S. Handcock, University of Washington. NSF grant BCS 01-20024.



# Opportunities



## A. Linked Observing Systems for Enhanced Research Capacity

Observations form the building blocks of environmental science and engineering. With the International Earth Observation Summit in 2004, governments world-wide acknowledged a vital need to detect, measure, and predict environmental changes and their potential impact. A comprehensive, coordinated, and sustained Global Earth Observation System of Systems (GEOSS) presents an opportunity for participating governments and the international scientific and engineering community to work together to understand and address environmental questions through improved observational capabilities. NSF can have a significant impact on U.S. participation in GEOSS by contributing to and advocating for strong science underpinnings.

NSF advances fundamental process-based research and development of integrated observing systems and cyberinfrastructure. NSF currently supports a variety of observing systems including EarthScope, Long-Term Ecological Research sites, coastal and open ocean observatories, and long-standing meteorological and seismological networks. Emerging initiatives, such as the National Ecological Observatory Network, Ocean Research Interactive Observatory Networks, HydroView, and Collaborative Large-Scale Engineering Analysis Network for Environmental Research, will further address pressing scientific questions and complement the capabilities of existing environmental observing platforms. The data to be derived from these observing systems will promote new interdisciplinary collaborations, models, and innovations. Because they are open systems, they may interface with those deployed by other agencies and countries, ensuring access by the broader scientific and engineering community.

The AC-ERE identifies three main challenges facing observing systems:

- moving from global measures to more precise regional measures that cover large geographic areas.
- developing measurements that lead to a better understanding of the linkages between human and natural environments and, specifically, developing a new generation of models built around the spatial attributes and dynamics of anthropogenic influences on natural systems.
- ensuring that the measurements, models, and analyses of environmental change provide forecasts that can better inform decision-making.

The next generation of tools and devices—and the systems and infrastructure in which they are embedded—will need to characterize both the environmental response to anthropogenic perturbations from the molecular to the global scale and the feedbacks to and responses from social systems. However, measurements alone are not sufficient. Scientists and engineers need to define what should be measured and how these measurements relate to understanding of interconnected environmental processes. Further, the community needs to develop approaches that integrate data from different observing systems, for instance, by linking land- and ocean-based sensor networks with satellite-derived information. Additionally, the utility of these data can be enhanced by improved visualization capability. Visualization is a way to link various kinds of observations and can be used to more efficiently convey results to decision-makers, students, and the public. Finally, the data from observing systems will enable the development of mathematical models.

## Agricultural Products

Increased use of biomass for energy- and bio-based products has great potential to help our nation reduce its dependence on fossil fuels and to decrease the amounts of agricultural pollutants seeping into our aquifers and waterways. Scientists at Iowa State University are following the life cycle of a polyester produced from corn, from its production through its use, to its final breakdown and dispersion to assess economic and environmental impacts. This project has brought together representatives of government, industry, and the research community to review the state-of-knowledge of the impacts of bio-based materials and work to build a consensus regarding appropriate assessment methods for bio-based products. The project has also included implementing an authentic, inquiry-based teaching module on bio-based products to enhance understanding of materials used in our society. Top photo: courtesy of Robert Anex, Iowa State University. Bottom photo: contour strip cropping, alternating bands of corn and alfalfa in a field on the Iowa-Minnesota border in Allamakee County by Tim McCabe. NSF grant BES 02-24006.



Models and simulations validated and improved through comparison with comprehensive and precise observations will enhance our ability to forecast environmental change.

To maximize the benefit of these investments, the development of extended observing systems must be coordinated with research on new sensor technology and environmental cyberinfrastructure. The former includes the use and development of well-calibrated systems capable of continuous observations and online adaptation to reconfigure sensing systems in response to environmental signals. Environmen-

tal cyberinfrastructure supports not only integrated access to data flowing from these observing systems, but also to the wealth of environmental data held in existing databases. A challenge is to manage and maintain access to these large databases and data arrays over extended periods of time. Together with the development of new, sophisticated models and advanced data assimilation techniques, these technologies will lead to powerful methods for testing hypotheses about environmental dynamics and predicting how environmental processes change over many spatial and temporal scales.

## B. Multi-Scale Science and the Human Context

Many complex environmental problems can only be addressed by integrating observations and processes across multiple spatial and temporal scales. For example, understanding ozone depletion requires consideration of at least three diverse elements: rapid chemical reactions occurring on the surface of ice particles in polar stratospheric clouds, the annual-scale global atmospheric circulation that drives cloud production, and the anthropogenic production of ozone-depleting gases over decades or longer. The role of humans as drivers of environmental change, and the effect of such change on human well-being are critical elements of research. Although the general issue of scale is a common theme in environmental research, explicitly bridging physical and social scales in the study of CES is an important research frontier.

The AC-ERE specifically identified two conceptual challenges to developing an inter-scalar perspective of complex environmental systems: (1) synthesizing and modeling across scales to understand how processes at different scales interact and (2) focusing on humans and their socioeconomic systems to examine and interpret the specific cross-scale environmental processes that are important to them.

Understanding how environmental change affects systems at the human level provides insight into the significance of environmental processes occurring at other levels. For instance, threats to public health from bacterial contamination are a pressing public concern. Understanding the persistence of pathogenic bacteria in coastal areas requires scaling up from microbial population dynamics and scaling down from weather and land-use patterns. Relating environmental processes to humans in this way allows scientific research to inform environmental management and, as an additional benefit, to improve public understanding and perception of science.

The challenge of synthesizing data and understanding across many scales is the formulation of theories that include key variables in such a way that measurements of linear, non-linear, and complex relationships can be made. In addition, how scale itself emerges as an important property of CES needs to be addressed. The AC-ERE encourages new research that will improve understanding of *a priori* linkages across multiple scales and the development of cross-scale theory that is explicitly testable.

## C. Water and Complex Environmental Systems Research

All human and natural systems are influenced by the distribution, abundance, quality, and accessibility of water. Water links and integrates human and natural systems as it moves above, across, and through the Earth. With continued human population growth and the uncertain impacts of environmental change, ensuring an adequate quantity and quality of freshwater for sustaining all forms of life is a growing challenge. Integrated, multidisciplinary, and multi-scale water-related research is necessary for meeting this challenge.

At a recent interdisciplinary workshop, *Water: A Complex Environmental Challenge at the Intersection of Human and Natural Systems*, scientists and engineers with a breadth of expertise discussed the current state of knowledge and identified important pathways for advancing understanding of water in the context of complex environmental systems. The AC-ERE supports the conclusions of this workshop. Typical approaches used to investigate aquatic systems tend to only advance knowledge of that particular system. To move be-



yond the limits of case-by-case studies, greater emphasis is needed on the development of theories and concepts that are transferable among systems. Theory development requires studies that focus on achieving a mechanistic understanding of environmental processes. This understanding can be achieved through manipulative experiments and modeling activities that elucidate important processes. Fueled by advances in observing tools and systems, data integration and synthesis activities are also essential.

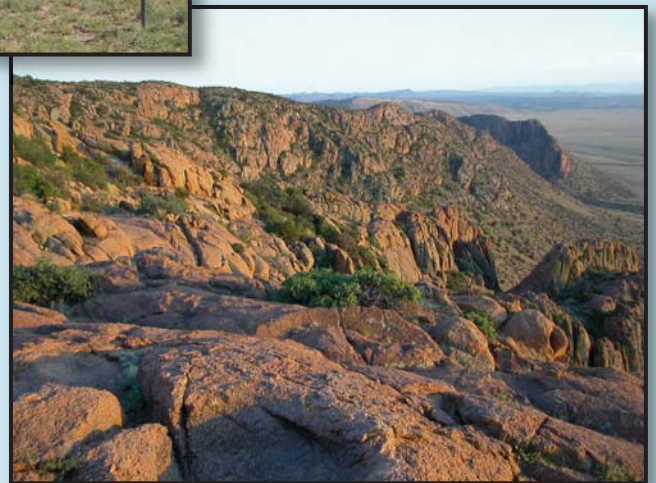
The AC-ERE recommends that NSF focus on water as a unifying theme for CES research. Organizing around a pervasive environmental component may provide a model for future

research campaigns. Because it is a critical resource whose availability strongly impacts human health and economic development, answering questions in this domain will advance scientific understanding while addressing urgent societal issues. Water-related research requires enhanced understanding of processes at environmental interfaces, approaches for integrating across scales, including social scientists in the development of truly integrative research questions, and improved coupling of biological and physical processes. Collectively, this research will advance the ability to forecast and plan for changes in water systems. Resulting methods can then be applied to other potential foci for CES research, such as land use, energy, and climate.

## New Mexico's Drinking Water is 50 Years Old

The Los Pinos Mountains of New Mexico are about 9,000 feet high, while the Rio Grande River courses through the valley almost a mile below at an elevation of about 4,800 feet. Precipitation in these mountains doesn't all run downslope, nor does it all evaporate into the atmosphere. Scientists long believed that the downslope distance from the mountainous highlands to the river valley was too great for recharge from rain falling on the highlands to support subsurface flow to the river valley.

New research suggests that rainfall and snowfall over the mountains in the basin and range area of New Mexico do in fact play an important role in recharge of the water table and the Rio Grande River. As input to a computer model used to simulate groundwater movement in Central New Mexico, a scientist from Pennsylvania State University measured several environmental variables at the study site (e.g., rainfall, snowpack, evaporation, altitude), and calculated porosity and conductance values of the local rocks. The simulation suggested that the time between rainfall on the mountains and ultimate recharging of the riverine water table was about 50 years. The implications of this research is that a major drought (low precipitation for several years) may not be observed in the Rio Grande for many decades. Photos courtesy of Christopher Duffy, Pennsylvania State University. NSF grants DEB 02-17774 and EAR 98-76800.



## D. A New Generation in Environmental Research and Education

Environmental challenges affect all populations and landscapes and therefore can be used to engage students and the public in the scientific and engineering enterprise. If the environment is used effectively to increase interest in science and engineering, the emerging ERE work force will include the best and most creative minds from all populations. The diversity inherent in that outcome is necessary to expand the playing field and allow new ideas to flourish, novel challenges to be identified, creative solutions to emerge, untapped intellectual potential to be harnessed, and a new generation of leaders to come to the forefront. As the NSF Deputy Director, Joseph Bordogna, observed in discussing the development of the scientific and engineering workforce:

*“[It is not]...about the total number of scientists and engineers the nation may or may not need. It’s easy to get distracted by trends and statistics cited in the news and debates about whether the demand for science, engineering, and technological workers is greater or less than the supply. It IS about including a larger proportion of women, underrepresented minorities, and persons with disabilities in the scientific workforce, no matter the size of that workforce. Whatever the numbers turn out to be, we need a robust and varied mix, and that means broadening participation...”*

In the educational arena, ambitious changes to curricula are needed that reflect the integrated aspects of environmental science and engineering, emphasizing the interdependence of human and natural systems. Complex environmental systems present an ideal avenue for developing new educational models based on environmental science that, if adapted imaginatively to the array of educational settings in the United States, could inspire students at all levels—but especially at early ages—and from all populations. Even the incorporation of environmental science into traditional courses can have profoundly positive effects on students’ enthusiasm about science and their recognition of the interconnectedness across traditional disciplines.

At the undergraduate and graduate levels and among young faculty, training and experience must include exposure to interdisciplinary research and hands-on and field experiences using cutting-edge technology. Additionally, mentoring throughout the educational and early career process creates a supportive and challenging educational atmosphere that promotes persistence in scientific and engineering careers. Only through these and similar efforts will the transformation to a new kind of researcher equipped to respond to environmental research challenges using diverse interdisciplinary methods and techniques proceed.

At the institutional level, structural changes must continue to be made in order to create a body of researchers who can better address the complex interactions within natural systems and between humans and the environment. New interdisciplinary programs and connections need to be fostered among traditional departments of science and engineering, including those in the social sciences. The institutions that will lead this emerging interdisciplinary focus will be those that support faculty who participate in CES research and education and recognize these contributions in the tenure and promotion process. Additionally, institutions will need to encourage and develop new leaders in these integrated research fields. Purposeful activities that promote new ideas, brainstorming, intellectual discussions, and exchange of knowledge across traditional departmental and college boundaries will enable these changes. NSF is in a prominent position to catalyze these institutional transformations.

## Environmental Inquiry: Learning Science as Science is Practiced

Scientists at Cornell University collaborated with teachers and educators to develop a set of in-depth, interdisciplinary, grade 9-12 instructional modules that focus on the application of the four process standards (from the National Science Education Standards)—Science as Inquiry, History and Nature of Science, Science and Technology, and Science in Personal and Social Perspectives—to environmental toxicology. Students using the materials will be investigating environmental problems relevant to their own lives. The modules include activities designed to engage students in three levels of inquiry: (1) open-ended laboratory exercises that focus on building skills and understanding science concepts, (2) exploratory investigations that give students the opportunity to investigate variables related to their initial laboratory exercise, and (3) controlled experimental research that uses the results of explorations to define a controlled experiment with independent variables. As part of the program, students learn to communicate their results to scientists and to the wider lay community. The modules developed also include materials designed to assist teachers in making the transition to inquiry-based science and to other aspects of the science reform movement. Photos courtesy of Marianne Krasny and Nancy Trautmann, Cornell University. NSF grant ESI 96-18142.



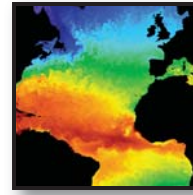
## E. Knowledge for Use: Effective Communication of Complex Environmental Systems Research

The AC-ERE believes it is imperative that CES research support society in direct and tangible ways. Environmental scientists and engineers need to connect their research to public concerns and effectively communicate scientifically cogent information. Scientists and engineers must ensure that there is clear public understanding of their work and take responsibility to see that it enables sound environmental decision-making. The intersections between research and society are numerous and include technological development directed toward the reversal of environmental degradation, understanding of harvested ecosystems to effectively manage natural resources, explorations of the effectiveness of remediation and environmental management, and studies that improve understanding of the ways that individuals, groups, organizations, and institutions interact with each other and with natural environmental systems. Improved understanding and

environmental forecasts enable governments and stakeholders to develop, implement, and evaluate environmental policies and prepare for natural hazards and environmental changes.

To be effective, interdisciplinary researchers and academic leaders must develop effective communication skills to reach diverse audiences, aided by advances in a variety of technologies from visualizations to models. Specific training in communication should become a part of the career paths of all young scientists and engineers. NSF can continue to promote communication by strongly encouraging and rewarding investigators who effectively disseminate their findings to the public, directly involve the public in their scientific and engineering investigations, and ensure that their research is used to support more effective decision-making.

# Pathways



Although there are many mechanisms that NSF could use to support improved environmental research and education, the AC-ERE has identified four that are particularly important for the future.

## Varied Award Sizes

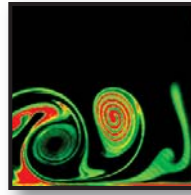
The funding mechanism for interdisciplinary research on CES has emphasized large, collaborative-team research grants, such as those awarded in the BE competitions. Although this approach has been successful, assembling and managing large teams of researchers with broad expertise can be onerous. Due to grant size and tenure-evaluation concerns, this format may discourage younger, less-experienced researchers from taking the lead or participating in this type of interdisciplinary research.

**Recommendation:** Team efforts should continue, but they should be only one of a broader spectrum of support mechanisms. It is vital that new investigators have an entry point to the interdisciplinary research and funding process. Therefore, there should also be opportunities to compete for small awards and opportunities that specifically target new investigators. This variety will provide greater flexibility than is currently available.

## GLUE Grants

NSF spends approximately \$1 billion a year on environmental research and education through a wide range of programs from across the agency. Developing mechanisms that could relate or knit together research from these numerous grants could provide a synergy and robustness to ERE at a low cost.

**Recommendation:** A small grant program should be developed to link together funded projects to leverage disciplinary research programs. This program could integrate projects funded from different NSF divisions or even from different governmental agencies. Aptly named GLUE (Grants to Leverage Understanding of the Environment), this program would provide an incentive for the community to coordinate research, build networks, and create synergy from what would otherwise be isolated projects.



## Synthesis Opportunities

The CES report highlighted a pressing need for synthesis activities to advance the frontier of knowledge about complex environmental systems. Extensive amounts of environmental data have been collected across many scientific and engineering research projects. These data represent a vast underutilized resource, as they are rarely synthesized across disciplines.

**Recommendation:** Opportunities for synthesis should be promoted throughout the full range of award sizes. Funding centers is one mechanism that can be used. Centers can support synthesis activities that are difficult to accomplish in the short time frame and small scale of standard grants.

## Data Accessibility

Although much data on the environment have been collected, they are not widely available. Observing systems and networks are being designed to answer questions that require integration of data across a wide range of temporal and spatial scales. Thus, it is critical that environmental data collected by individual investigators and observing networks are accessible to all research communities.

**Recommendation:** Early in the planning stages, mechanisms should be developed to ensure long-term funding of the data infrastructure needed to successfully operate observing systems and networks. These observing systems and networks must be constantly reviewed by the community to ensure that as new systems are proposed, developed, and integrated, issues of data continuity and transferability remain critical components in development and deployment decisions.

# Conclusion



The AC-ERE commends NSF for progress made in the past decade in supporting highly interdisciplinary environmental research and education. We urge the Foundation to continue this progress by developing new ways to build capacity in coupling human and natural systems, in interdisciplinary research and training, and in observing systems, data integration, and scaling. We encourage NSF to consider water as an important theme, find ways to create synergy among programs, and to take the opportunity to harness the current energy of the science and engineering community to increase public understanding, improve environmental decision-making, and develop and attract a more diverse workforce.

The AC-ERE has witnessed an incredibly rapid growth in NSF programs that support complex environmental research and education and a growing enthusiasm in its community of scientists, engineers, and educators. The AC-ERE recognizes the need to continue to promote the interdisciplinary research that the community has come to embrace. To this end, the AC-ERE will continue to encourage the science and engineering community to engage in and enrich the work of this committee by providing insights and ideas.

In the coming years, the AC-ERE will focus on some of the new and exciting priorities emerging across the federal government and ways for NSF to partner with other agencies. For instance, in keeping with the strategic focus on observatories, the new GEOSS initiative provides a framework for multi-agency collaboration. Moreover, it is hard to imagine a system of observatories without clearly defined science objectives and strategies for measurements, including where and how often to make them. Finally, it is increasingly clear that environmental science and engineering can, and should, lead to societal benefits, such as increased global security, improved natural hazard forecasting, and advances in environmental remediation and mitigation technologies.

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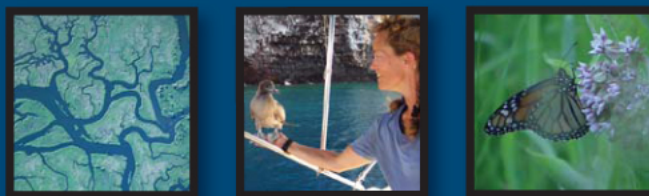
- Margaret Leinen, NSF Assistant Director for Geosciences

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