Transitions and Tipping Points in Complex Environmental Systems

A Report by the 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 the 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 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.

Additional information can be found at: http://www.nsf.gov/geo/ere/ereweb/advisory.cfm

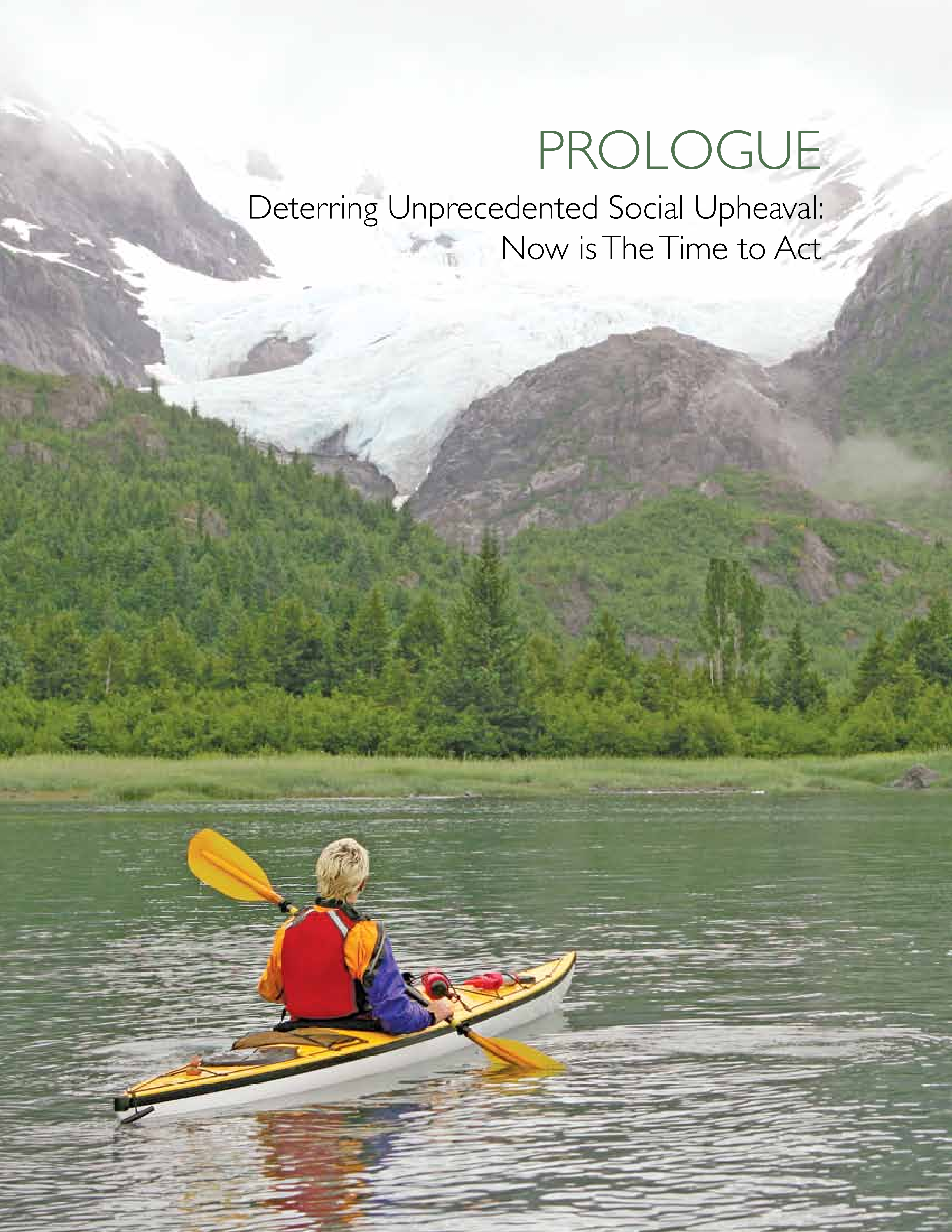
JUPITER

Transitions and Tipping Points in Complex Environmental Systems

MIKE USHER, NSF

PROLOGUE

Deterring Unprecedented Social Upheaval: Now is The Time to Act



Shishmaref is a village five miles from the Alaskan mainland on Sarichef Island in the Chukchi Sea. Global warming has resulted in less ice in the Chukchi Sea, ice that provides natural protection to the island's coastal shores against powerful storm surges. While the coastlines are eroding faster the land underneath the village is falling into the voids caused by melting permafrost. Shishmaref is sinking.

NOAA

Sarichef's coastline is receding at up to three meters annually and barricades have failed to keep the ocean at bay. Buildings and roads have been lost to erosion and basic infrastructure is being compromised. Winter ice on the Chukchi Sea is softer and less stable, affecting ocean travel and impacting the indigenous Inupiaq people's traditional hunting and fishing activities, jeopardizing both their safety and food supply. The village's very existence—physical and cultural—is at risk.

Shishmaref is both outpost—offering haven to explorers and seafarers for centuries—and frontrunner—as one of those places most affected by climate change. The increasing risk to property and lives has forced the community to consider abandoning their island and begin planning to move their village to the mainland. Even if they can find a suitable location and raise the estimated $180M to finance the move, the cultural and social integrity of the community will be intimately affected. The Inupiaq describe their fate as a harbinger for the rest of the world.

The vast region encompassed by Alaska is on the front lines of climate change, experiencing a rise in average winter temperatures of more than four degrees Celsius in the last 60 years and potentially another five to nine degrees by the end of this century. The state's arctic and subarctic ecosystems already are transforming from what Americans recognize as The Last Frontier state. Spruce bark beetles have responded to changing ecological conditions by infesting the forests, wiping out millions of hectares of spruce trees on the Kenai Peninsula in the past two decades, the largest loss ever recorded in North America caused by this beetle. In today's warmer, drier weather Alaska is suffering its most destructive fire seasons, claiming millions of hectares of forest and the trend is clearly showing increased frequency with each passing year. Freshwater bodies throughout Alaska are evaporating or draining at unprecedented magnitudes, changing the landscape.

MICHELLE KELLEHER, NSF

The people of Alaska will respond to these environmental challenges in ways that may alter their culture and economy. But there is no clear roadmap of consequences to serve as guide for the choices they face—choices we will all eventually face. They are decisions made by people everywhere, individually and collectively, decisions motivated by incentives and rewards that are local and short-term, that in aggregate cause environmental changes that are global and long-term.

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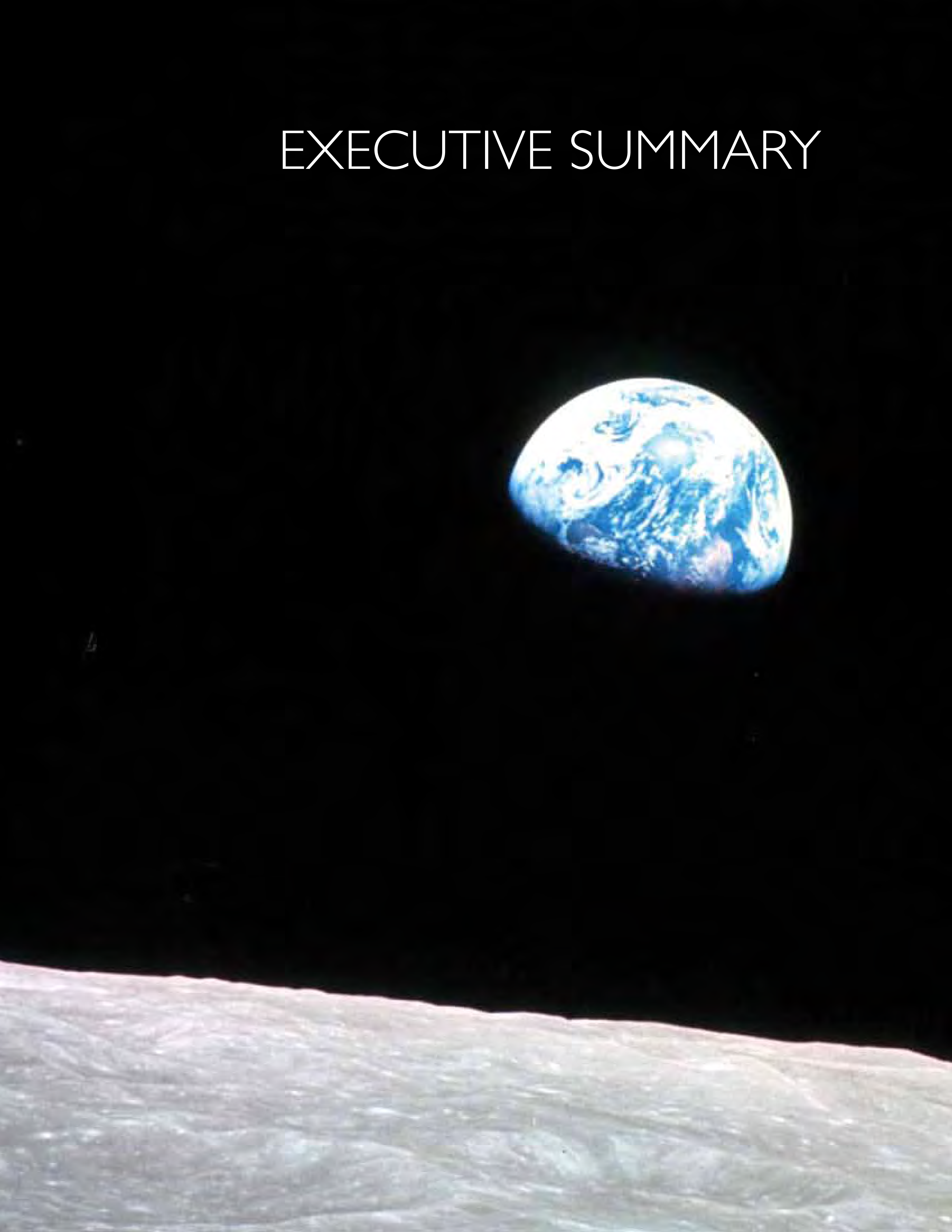
EXECUTIVE SUMMARY



THE ADVISORY COMMITTEE for Environmental Research and Education advises NSF on its support for research and education in the environmental sciences, which figure prominently in NSF's Strategic Plan 2006-2011.[1] A short 3 years into that plan, we conclude that fundamental research and widely dispersed education are not progressing at the pace required by the magnitude and urgency of the environmental challenges that face this nation and all societies. NSF should increase its commitment to its investment priorities to: "Foster research that improves our ability to live sustainably on Earth" and "To strengthen our understanding of the links between human behavior and natural processes."

The NSF is well-suited to lead a reinvigorated scientific initiative in the environmental sciences. The agency already provides broad support for the disciplines that are critical for environmental science, including the behavioral and life sciences, the earth and atmospheric sciences, the social sciences, and the mathematical, physical, engineering, and information sciences. The substantial challenges facing us in the environmental sciences will require research that integrates all of these disciplines. Accordingly, we recommend NSF place a high priority on interdisciplinary activities that integrate these components. The goals of this effort must be to provide a better understanding of complex environmental systems, a higher level of environmental literacy in the public, and a stronger foundation for informing policy decisions for addressing global environmental issues.

NSF cannot change our collective approach to environmental issues by itself. The challenges are multifaceted in nature and large in scale and NSF must join with other agencies to promote the strongest effort that the community's scientific talent can muster. Moreover, interdisciplinary priorities for NSF and other agencies will not achieve all that they could achieve if the institutional practices within the research and education communities are not adapted to facilitate interdisciplinary action.

The need for equitable, ethical, and sustainable use of Earth's resources by a global population that nears the carrying capacity of the planet requires us not only to understand how human behaviors affect the environment but also how human behavior changes in response to changes in the environment or perceptions of environmental status. The committee recommends that the approach to environmental literacy bridge the gap between the academics who do the research, the tool developers who design curricula and applications, and the communicators and educators who translate the science into terms that can be broadly understood by policy makers and the public.

These goals of bold interdisciplinary research and public engagement will be difficult to accomplish and conducting research and education via a model of "business as usual" will be insufficient. Current practices in academic and government institutions, with their traditional disciplinary funding and evaluation mechanisms, often inhibit the truly innovative and integrative science and education the nation needs. NSF should adopt organizational and review strategies that promote interdisciplinary innovation and ensure that programs funded for interdisciplinary activities have the longevity

[1] National Science Foundation. 2006. *Investing in America's Future Strategic Plan FY 2006-2011.* NSF 06-48, 24pp.

NASA

necessary to attract scientists to work collaboratively across the disciplines.

CHALLENGE: INCREASING STRESS ON THE PLANET

The world is at a crossroads. The global footprint of humans is such that we are stressing natural and social systems beyond their capacities. We must address these complex environmental challenges and mitigate global scale environmental change or accept likely all-pervasive disruptions. Rapid development and growth of human populations are causing changes to natural ecosystems and biodiversity loss of a magnitude and scale not seen before during human existence. Environmental challenges are increasingly of a global scale; while many changes appear small individually in aggregate they have large and even synergistic effects. At the same time technological advances are changing lifestyle and social norms on every level as well as livelihood patterns. As these socioeconomic systems have become more globally connected and interdependent so too have their interactions with environmental systems. These changes in environmental and social systems represent serious threats to our economy, security, and human health.

DHS

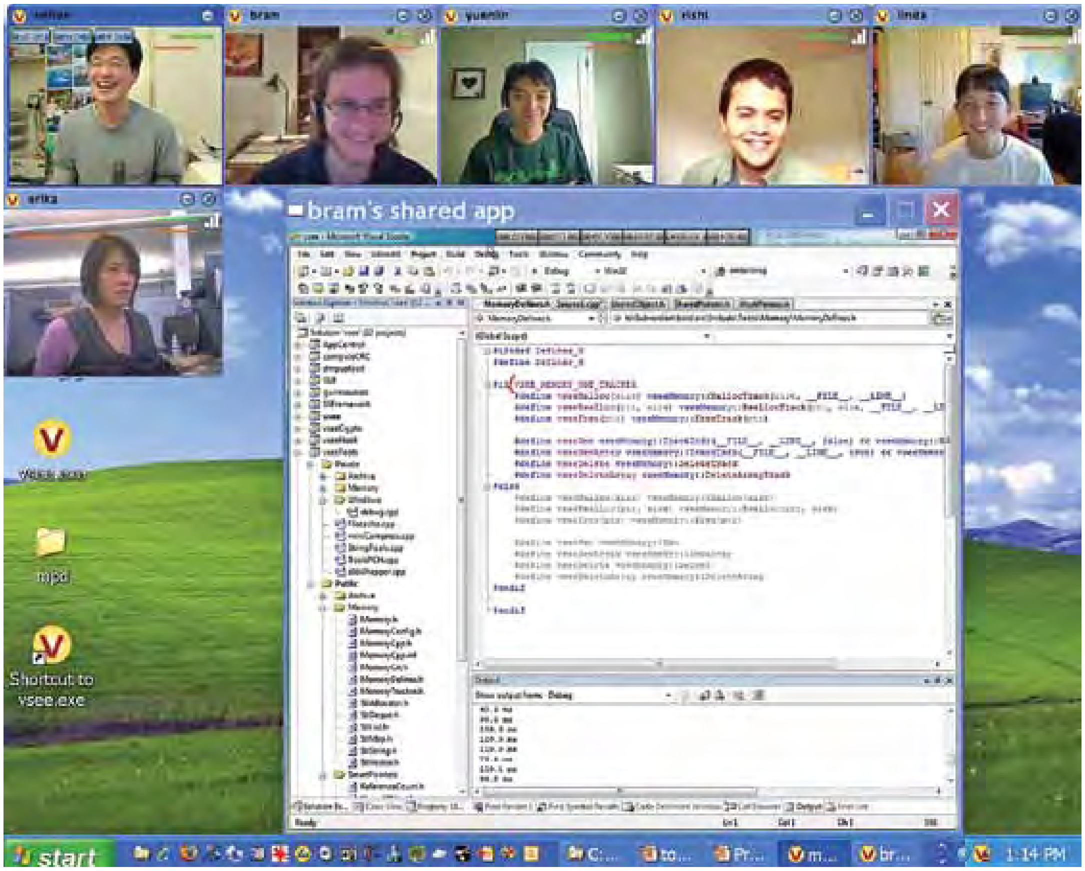
CHALLENGE: LITTLE TIME TO ACT

The rate of environmental change is outpacing the ability of institutions and governments to respond effectively. Issues that previously were addressed at the local level are no longer adequately understood without a regional, continental and, increasingly, global perspective. While we recognize the direct connection between local human activities and global environmental changes, the feedbacks of that change on regional ecological and social systems are poorly understood. The issue is not just spatial scaling; there is also the temporal disconnect between environmental changes and the human actions that cause them and the policies designed to address them. We must rapidly increase our ability to forecast change in globally connected natural and human systems, or find ourselves responding increasingly to crises.

> The global footprint of humans is such that we are stressing natural and social systems beyond their capacities.

CHALLENGE: NEW RESEARCH NEEDED

Environmental science must move beyond identifying issues and toward providing sound bases for the development of innovative solutions, effective adaptation, and mitigation strategies. To accomplish this goal we urgently need to expand our capacity to study the environment as an integrated system that includes the human dimension. Humans are inextricably embedded within supporting environmental systems. To understand this coupling of natural and human social systems, we must advance general concepts such as ecosystem services and describe the processes that link natural systems, from local to global scales, with human systems from individuals to collectives. Incorporating the



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human component will require long-term, regional-scale research that addresses how individual behavior, demography, and social systems respond to changes in the functioning of environmental systems. While scientists from every discipline can make significant contributions, studying the components of environmental systems in isolation from each other is neither adequate nor meaningful. To address the environmental challenges that confront us we must find ways to integrate and synthesize data from diverse fields into a whole-systems perspective, taking into account the complications of interactions occurring on different spatial and temporal scales. We need to better anticipate thresholds of rapid transition—tipping points—in complex environmental systems. Natural and human systems alike are changing in ways that are poorly understood. How far and in what ways can these systems be stressed before they reach tipping points, i.e., undergo rapid transition to new states with unforeseen consequences? We must grapple with the complexity that emerges from the processes inherent in coupled natural-human systems to understand and, where possible, forecast and manage their dynamics in the context of a rapidly changing environment.

OPPORTUNITY: A PERVASIVELY NETWORKED PLANET

Developments in cyberinfrastructure are changing how we conduct science and how scientists interact with each other and with the public. The tremendous potential of sensors and observational networks to gather consistent data on many variables is critical to responding to the environmental challenges


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we face. These networks have the capability to monitor conditions across broad spatial and temporal scales and allow us to examine new kinds of variables, including those in the social sciences. Cyberinfrastructure enables the sharing of vast amounts of data which broadens the involvement of people and institutions and encourages collaboration and open source innovation. This fosters the interdisciplinary connections and synthesis needed to address complex environmental challenges. Just as the first view of planet Earth from space helped crystallize a global perspective and an environmental awareness, the advent of global, interconnected, and interdisciplinary data networks will be important in fostering international, collective action to address environmental problems.

OPPORTUNITY: ENGAGE THE PUBLIC

Without an informed knowledge base, citizens and policy makers are ill-equipped to make responsible decisions about our environmental future. Although elements of environmental science are included in current formal and informal education, most efforts fail to integrate them into a framework that promotes environmental literacy through understanding of the linkage between natural and human systems. Differing perceptions and values on the relationship between


MARA CHERKASKY

humans and environment are the foundation upon which cooperative behaviors critical to managing the environment must be built. The networked world opens up new opportunities to engage the public, increase environmental literacy, and change the way we approach environmental science. Within this decade over 5 billion people will be connected through cell phones and the Internet. This comes at a time when many younger people are spending less time in the natural environment.[2] A connected generation is growing up with a new capacity for collaboration and interest in social experimentation enabled by new computing and communications platforms. In this digitally connected and socially networked world, people are no longer passive consumers of information. They interact with and contribute to information and co-create solutions in cyberspace. This invites exciting new avenues for learning opportunities that meaningfully connect people to their environment through data and models. It is time to ask how we can best promote environmental literacy by engaging a cyber-connected society for the benefit of environmental science.

OPPORTUNITY: NSF UNIQUELY POSITIONED

NSF is the only federal agency that supports all fields of science and engineering necessary to understanding complex, coupled natural-human systems. Through NSF's efforts to encourage interdisciplinary research, the agency is uniquely poised to foster innovative research that improves our ability to live sustainably on Earth. But the pace of this interdisciplinary research is woefully insufficient given the urgency of our

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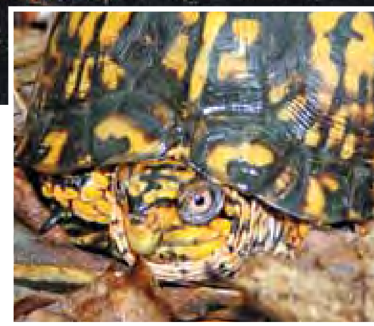


PENELOPE FIRTH, NSF

environmental challenges. If NSF is to be an effective agent of change in environmental research, greater priority must be given to advancing an integrated approach to earth systems and addressing the complexity of coupled natural-human systems from local to regional to global scales.

Recommendations

I It is imperative to increase our understanding of coupled natural-human systems through increased support for broadly interdisciplinary environmental research. Such research should be responsive to the urgent needs of society for knowledge that addresses our environmental challenges and informs a more sustainable way of life. We must understand better the complications of processes that operate on different scales and the feedbacks that can trigger abrupt change in environmental systems. Such understanding will maximize our ability to predict thresholds of change, design remedial actions that move us away from those thresholds, and identify

[2] Richard Louv. 2005. *Last Child in the Woods: Saving Our Children from Nature Deficit Disorder.* Chapel Hill: Algonquin Books.

ALEJANDRA RESTREPO-CORREA, FLORIDA INSTITUTE OF TECHNOLOGY

pathways of adaptation in response to change. To this end, NSF's directorates and offices should all adopt the study of coupled natural–human systems as an important part of their core missions, from the study of the physical and biological factors that drive these systems to an understanding of the human responses to alteration in systems states.

2 NSF must evolve from its primarily discipline-centered organization to one that better promotes and supports interdisciplinary approaches, and attracts more scientists and engineers to engage in collaborative and integrative research and education that addresses the nation's environmental challenges. To achieve this, NSF must increase the size and longevity of funding programs that support broadly interdisciplinary research, i.e., programs that span multiple NSF directorates. Sustaining such programs on a time frame relevant to the career paths of individual researchers is necessary to facilitate cross-disciplinary dialogue and synergistic collaboration. The Dynamics of Coupled Natural and Human Systems, originally supported through the Biocomplexity in the Environment initiative, serves as a prominent example of this type of cross-directorate activity. NSF should explore additional models of promoting interdisciplinary research, including new partnerships with other federal agencies, foundations, and the private sector, and new ways of conducting peer review so as to foster more collaborative and innovative approaches.

3 NSF should lead the effort to ensure the implementation of a well-designed and integrated system of observational sensor networks that measure critical environmental variables as well as the changes in key human activities with environmental consequences.

CENTER FOR BIOMODULAR MULTI-SCALE SYSTEMS, LOUISIANA STATE UNIVERSITY

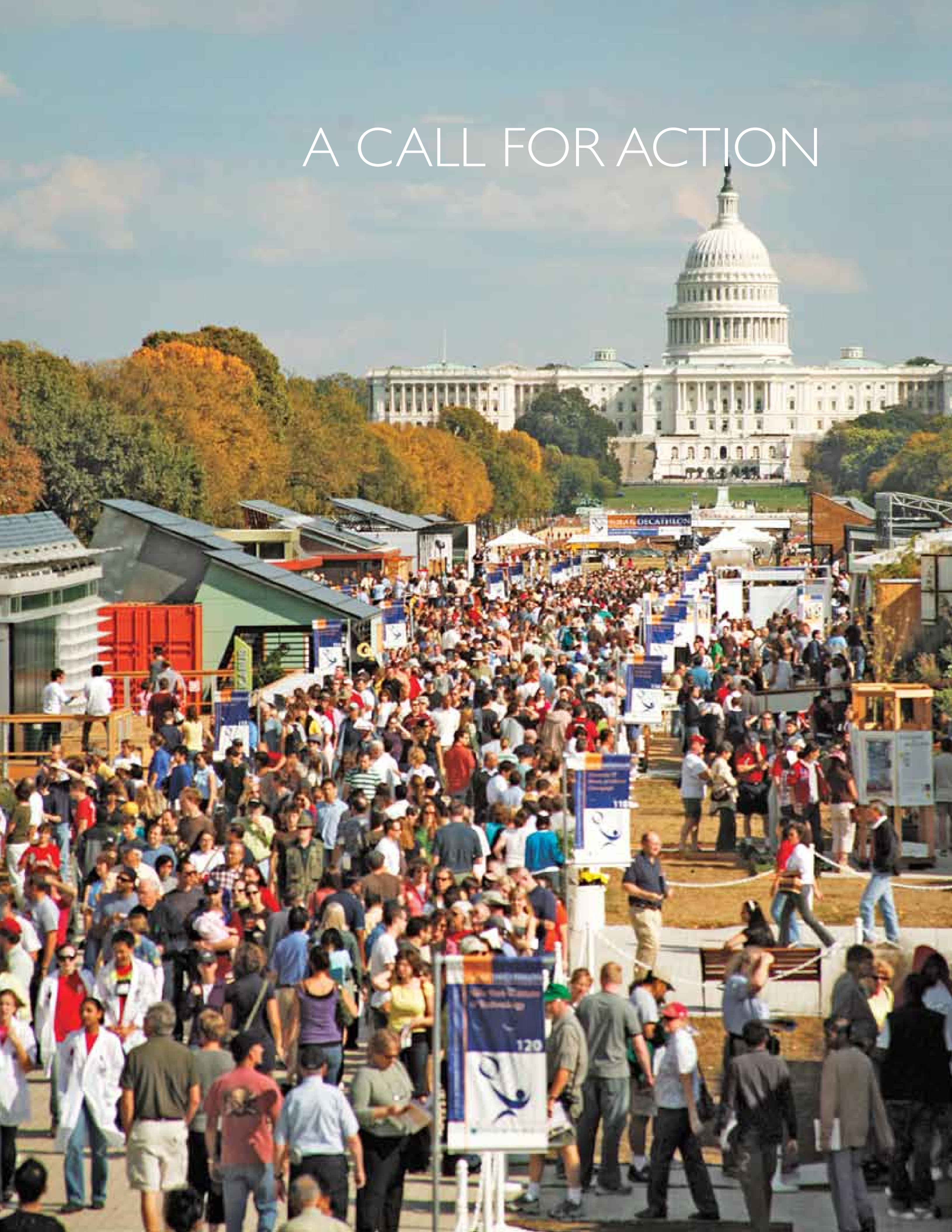
CHARLES NILON, BALTIMORE ECOSYSTEM STUDY LTER PROJECT AND UNIVERSITY OF MISSOURI-COLUMBIA

This effort should be well-coordinated with other federal agencies and governments to ensure that data can be shared across networks and to maximize the opportunities for synergy. The priority for NSF in creating environmental observatories should be to facilitate research needs, as stated above, and to better link site-based and experimental studies to long-term observations spanning regional to global scales. Related to this goal is a need to ensure long-term stewardship of data. NSF should require that all proposals provide plans for management, accessibility, and preservation of data to be collected during a project, and evaluate those plans as part of the peer review process.

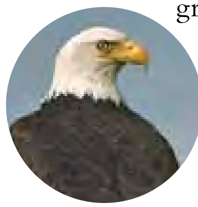
4 We must redouble efforts to promote new and participatory approaches to environmental education and public engagement through formal and informal venues. A higher level of environmental literacy is essential if we expect to persuade the general public to adopt behaviors that will help solve environmental problems. An environmental literacy framework grounded in basic concepts that integrate disciplines into a holistic perspective of Earth's natural and human systems should be developed for K-20 education and beyond.

5 We must help policy-makers develop a better understanding of complex environmental systems, an understanding that helps them appreciate the concepts of tipping points, the thresholds of large magnitude or abrupt change, and the socio-economic effects of severely altered environmental systems. Tools must be developed that assist stakeholders to visualize and synthesize data from multiple sources. We call for the advancement of decision support tools that integrate knowledge across disciplines to address long-term consequences. Policy-makers and the general public must be engaged in activities that lead to a better understanding of the interconnectedness of environmental challenges such as water availability, biodiversity loss, population growth, and energy demand, and of the uncertainties we face in making predictions in an era of rapid environmental and social change.

A CALL FOR ACTION



THE ADVISORY COMMITTEE for Environmental Research and Education (AC-ERE) serves to review and advise NSF on its support for research and education in the environmental sciences. The committee was established in response to a report issued by the National Science Board in 2000, "Environmental Research and Education for the 21st Century." That report recognized that environmental science and engineering are intrinsically multi-disciplinary and must involve all parts of NSF. Hence, the members of the AC-ERE are representative of all fields of research and education supported by the Foundation. A report was last issued by the AC-ERE in 2005 yet in the brief time since, the public's concern with rapid environmental change has grown, and with it a call for action. In this report, the AC-ERE reviews what new knowledge is most critical to address the environmental challenges that confront us.



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Environmental Challenges

The current state of the environment presents urgent challenges for scientists in the natural, social and behavioral sciences. Human actions have impacted all parts of the globe with resulting changes in the structure and functioning of environmental systems at all scales. Yet the public has been slow to acknowledge these changes and even slower to act. The costs of ignoring these changes, environmental, economic and social, may be catastrophic. While climate change is the most obvious illustration of this fact, it is not the only phenomenon. Population growth and technological changes alter the pattern of human settlement and livelihoods, creating inequalities and shifts in social norms which in turn differentially increase the demand for energy, food, and water and stress both socio-economic and environmental systems. Because environmental and social systems are strongly interconnected (i.e., coupled natural-human systems), stresses in one increase the vulnerability of both systems to disruptions. In this connected world, disaster in one region or system can too easily cascade to others. We need to understand which of the coupling relationships are loose and which are tight, the mechanisms that contribute to the resilience of coupled natural-human systems, and the feedbacks among their components and processes that link these systems at local, regional, and global scales.

When a system is pushed by natural or social stresses to a tipping point the feedbacks from that abrupt change can be unpredictable.

Our scientific appreciation for the complexity of interactions within coupled natural-human systems has grown vastly and so has our sense of urgency to understand and forecast change. We are at a time of unprecedented opportunity—and beyond opportunity, necessity—to address environmental and social challenges unprecedented in the history of modern civilization. Continuing to ignore these changes limits our abilities to mitigate or

KAYE EVANS-LUTTERODT/SOLAR DECATHLON

adapt to their consequences. Yet, the state of the science in understanding the dynamics of coupled natural-human systems is inadequate to make predictions about when and where sudden change will occur and how to use science and education to better shape our future.

Understanding of transitions, tipping points and abrupt changes in complex environmental systems will also benefit from greater involvement of mathematics and computer science in the environmental sciences as well as investments in cyberinfrastructure.

Understanding coupled natural-human systems and anticipating their behavior is complicated by several factors. First, human decisions and actions are difficult to model and involve a scale of interaction from individuals to larger social units and institutions. Further, the scale of decision making by individuals and institutions is generally local and short term, while the environmental consequences of human actions are regional and long-term. Adding to these scaling complications is the fact that cause and effect relationships play out amid multiple pathways that sometimes hide or modify interactions. When these interactions involve non-linear responses, changes in one aspect of a system may seem unrelated to changes in another aspect until a critical threshold is reached, i.e., a tipping point, beyond which dramatic transformations occur suddenly. Tipping points can occur in both natural and human systems and are difficult to predict. For example, at what point does cultural perception and behavior tip into awareness and then into actions? When a system is pushed by natural or social stresses to a tipping point, the feedbacks from that abrupt change can be unpredictable. In particular, the way in which humans interact with their environment may be changed irreversibly. This report calls for greater research emphasis on the complications of temporal, spatial, and behavioral scaling, on the rapid transitions that occur when a tipping point is reached, and on the ensuing feedbacks of that change in coupled natural-human systems.

Our largest challenges are based in complex environmental systems in which human effects are coupled with a variety of physical, chemical, and biological processes. Indeed, human effects may be pushing systems toward tipping points they might never have approached otherwise. While the social and natural sciences have historically influenced each other, their joint application to environmental challenges remains limited given their different epistemologies and foci. Yet it is the melding of these approaches that will generate the type of interdisciplinary, integrative research and education that are necessary to address our greatest environmental challenges. For example the notion of ecosystem services, which emerged from a joint consideration of ecosystem science and human values and economy, is an interdisciplinary concept to couple natural and social systems

The AC-ERE[3] and others[4] have called for greater emphasis on addressing real world problems through interdisciplinary research at intersections of the social, behavioral and natural sciences and engineering yet this call remains largely unanswered.

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[3] *Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century* (2003) and *Complex Environmental Systems: Pathways to the Future* (2005).
[4] J.P. Holdren. *Science and Technology for Sustainable Well Being.* Science (25 January, 2008) 319: 424-434.


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Interdisciplinary Opportunities

The scale and nature of environmental challenges requires expertise from a wide variety of disciplines, and dialogue and collaboration among scientists to achieve integration among these disciplines. Understanding of other major phenomena has advanced largely through interdisciplinary approaches, e.g., cognition or evolution. Interdisciplinary and integrative research will be especially important for understanding complex environmental systems that are "adaptive," that is whose components respond to the state of the system as a whole, as when fishing fleets change their efforts in response to the size and distribution of harvestable fish or the costs of fuel and marketing. A benefit of interdisciplinary engagement is that different and more innovative questions emerge than would be the case from any single disciplinary perspective. In this report we argue for integrated and interdisciplinary research as the best means of addressing the complexity of environmental systems.

Concurrent with the rising awareness about the scope of environmental change we see new interdisciplinary fields of science and engineering emerging. Geoengineering, which combines engineering with the geosciences and biology, has developed as an approach to mitigate the magnitude of large scale environmental change e.g., accelerating biological activity to drive biogeochemical systems in chosen directions, such as seeding the oceans with iron in order to accelerate removal of carbon dioxide from the atmosphere. Mitigation of environmental change will involve re-engineering numerous coupled natural-human systems. Urban centers, already housing half the human population, continue to expand. The engineering of urban infrastructure must consider its life time demands on materials and energy and seek to match these to what can be provided sustainably by Earth's systems. For example, water management systems are currently intimate parts of many ecosystems and engineering solutions to achieve sustainable water supplies will be needed on massive scales. An opportunity exists to better match the human systems that manage water use and availability to the scale of the natural systems providing this resource.

Understanding of transitions and tipping points in complex environmental systems will also require greater involvement of mathematics and

CEDAR CREEK ECOSYSTEM SCIENCE RESERVE

computer science in environmental sciences as well as investments in cyberinfrastructure. Mathematics is the fundamental tool for the study of dynamic systems involving nonlinearity and tipping points. Advanced computing extends the range and complexity of models that can be explored and thus improves predictive modeling at finer spatial and temporal scales. It is impossible to study complexity without the capability of advanced computing to open a world of simulation exploring the non-linear relationships inherent in complex environmental systems. Cyberinfrastructure supports the observation of real-time dynamics of complex systems through advanced sensors and observing systems, data integration, modeling, and visualization. This informs and enables the decision support and adaptive management potential for policy makers.

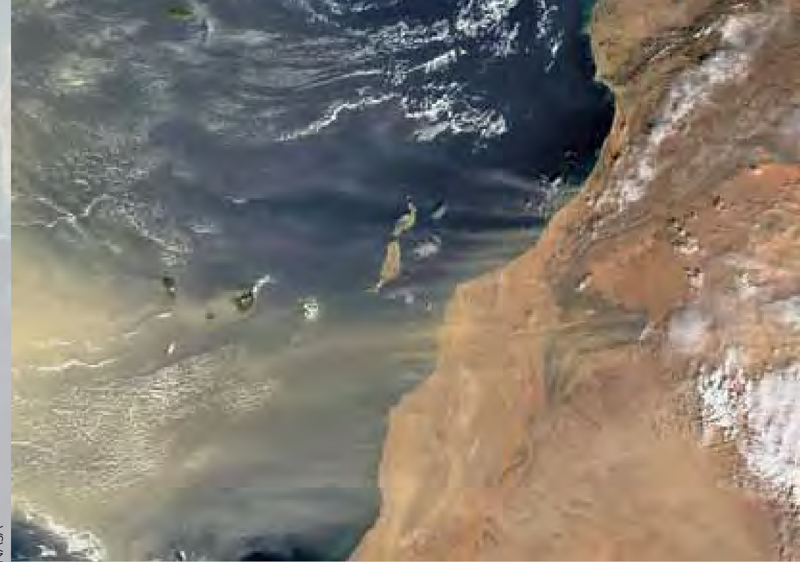
As our quest to understand planetary change accelerates, finding new ways of observing the environment, including human activities, at broad spatial and temporal scales increases in importance. Environmental observing systems such as the National Ecological Observatory Network (NEON), Ocean Observatories Initiative (OOI), EarthScope, Water and Environmental Research Systems (WATERS), and the Arctic Observing Network (AON), will provide new opportunities for scientists to study the processes that connect the atmosphere, biosphere, geosphere, hydrosphere, and anthroposphere at regional to continental scales. The cyberinfrastructure that makes these systems accessible online will serve to attract students, educators, and even the public to participate in research, conduct their own research with already existing large data sets, and monitor trends and events. Already, teenagers have discovered new asteroids, now named after them. As in astronomy, environmental data streams from global monitoring networks make participatory science a possibility for anyone with access to the Internet.

Studying the components of environmental systems in isolation from each other is no longer a meaningful approach.

Environmental observing networks may also promote more integrated, whole-systems research approaches. Studying the components of environmental systems in isolation from each other is no longer a meaningful approach. If we are to understand mechanisms that couple natural and human systems, we need to match the scale of observation of Earth system processes with the scale of observation of human behavior and social processes. Environmental observing networks, along with their shared databases, present opportunities for scientists to address processes linking different observational scales, and to synthesize across different types of data.

Earth: Our Planet As We Know (Knew) It

Over the past four billion years, driven by solar energy and internal heat, Earth has fostered the evolution of life in ways that created a system of feedbacks linking rock, water, atmosphere, and solar energy. The early advent of ocean organisms drove the removal of greenhouse gases from the atmosphere and supplied oxygen back to the atmosphere, creating the ozone layer that allowed the evolution of land organisms. A tight coupling of living and non-living systems continues to define the environmental systems of our planet.



NASA

Dust, Oceanic Phytoplankton, and Climate Change

A prominent example of the connections among systems on Earth and the potential for humans to alter them is the relationship between wind-borne dust deposition and phytoplankton productivity in the open oceans.

Dust from deserts, under-vegetated, and disturbed lands is scattered by winds over distances of tens of thousands of kilometers and areas of hundreds of thousands of square kilometers, reaching large areas of the open ocean. This long-distance dust is laden with iron, a necessary ingredient for phytoplankton production. Experiments have shown that additions of iron to patches of ocean can rapidly cause blooms of phytoplankton. And dust deposition accounts for the majority of iron input into the world's oceans.

Land use changes, particularly changes in the developing world, are altering global patterns of dust transport. The effects are not uniform. Urbanization can reduce soil erosion and dust transport to the ocean in some places. However, climate change is causing an expansion of deserts in many parts of the world. The increased demand for food is also stressing arid lands in developing countries and resulting in rapid soil erosion. This causes more iron-rich dust to be swept up and carried through the atmosphere. Iron-laden dust from Africa has been known to stimulate phytoplankton changes in the Gulf of Mexico that ultimately contribute to red tide blooms. Land use change on one continent can affect ocean ecosystems half a planet away.

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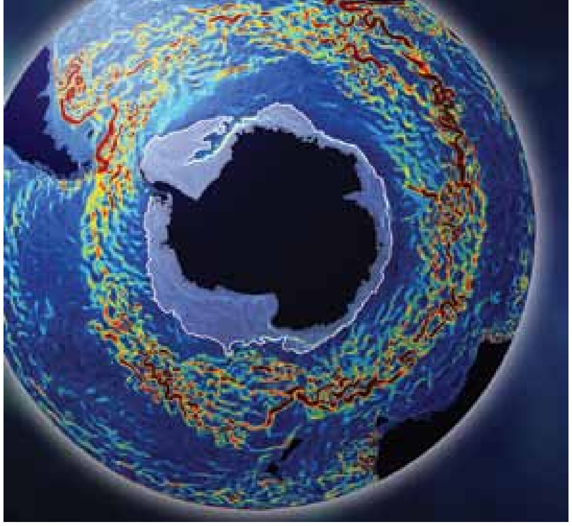


IMAGE COURTESY M. MAZLOFF, MIT;
SOURCE: SAN DIEGO SUPERCOMPUTER CENTER, UC SAN DIEGO

Dramatic short-term events—such as meteor impacts and volcanic eruptions—altered but never extinguished, life on Earth. Humans evolved on the planetary stage to become an integral part of this diverse ecological system of systems. With the birth of the Industrial Revolution and subsequent exponential growth of the human population our cultural activities became an influential force on Earth's system of checks and balances. We depend on the Earth; we are changing it; and now the rate of change is, like a car with its gas pedal stuck to the floor, accelerating. How can we control it?

Change is happening at rates that threaten our sustainable well being, and we are responsible.

Among the biggest environmental surprises of our lifetime was discovery of the size of the ozone hole over Antarctica, published in a paper in *Nature* in 1985.[5] The finding came as a shock to the scientific community. Although the mechanism creating it had been predicted since 1974,[6] the decline in polar ozone was far greater than anticipated. We soon learned of the close link between the widening ozone hole and the use of chlorofluorocarbon compounds (CFCs) in multiple convenience products. With this came the awareness that diffuse human activities could have global-scale impacts, including a potential to reverse the process. In 1987, nations around the world came together to sign the Montreal Protocol on Substances that Deplete the Ozone Layer.[7] The protocol called for CFCs and related compounds to be phased out. More than 190 countries have signed the agreement and evidence suggests it has been successful; the ozone layer is recovering.

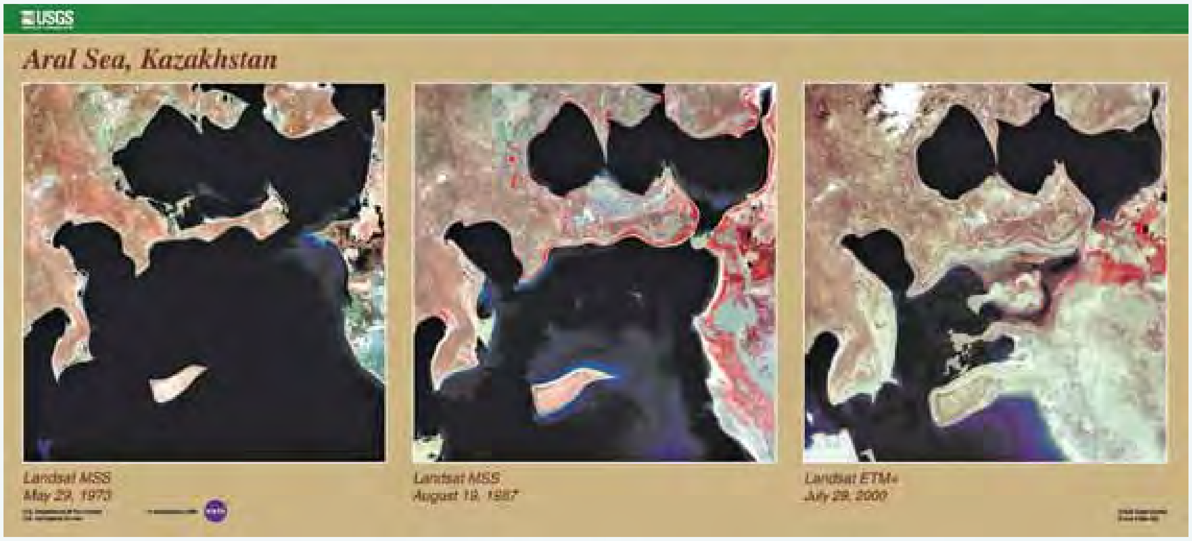
As the hole in the ozone layer demonstrates, the effects of human actions can have global-scale impacts on Earth's systems in relatively short time periods and the greatest impacts can be distant from the cause. Reports by the Intergovernmental Panel on Climate Change (2007)[8] underscore the point with respect to enrichment of the atmosphere with greenhouse gases. But other examples exist; nitrogen enrichment of global ecosystems, massive loss of biodiversity, acidification of ocean systems, and collapse of many of the ocean's fisheries are all examples of the global scale of environmental impacts caused by the pace of human population growth and development. Change is happening at rates that threaten our sustainable well being, and we are responsible.

The Rapid Progression of Our Environmental Challenge: A World Without Recent Parallel

Environmental change is not a new episode in the history of life. Earth's history is one of constant change in sea level, climate, available habitat, and atmospheric chemistry. Scientists have discovered close links between periods of environmental change and alterations in life on Earth. While the rate of environmental change

[5] Farman, J. C., Gardiner, B. G., & Shanklin, J. D. *Nature* (16 May 1985) 315, 207–210.
[6] M. J. Molina and F. S. Rowland, *Nature* (28 June 1974) 249, 810–812

[7] http://www.unep.org/ozone/pdf/Montreal-Protocol2000.pdf
[8] http://www.ipcc.ch/



U.S. DEPARTMENT OF THE INTERIOR, U.S. GEOLOGICAL SURVEY, NASA

A Disappearing Sea—
A Place Blighted

Since the 1960s the Aral Sea has been shrinking rapidly. By 2003, the sea had lost 75% of its surface area. Today it is only 10% of its former size. It has become the site of one of the largest human-caused environmental disasters on Earth, eventually affecting every one of Central Asia's ecosystems and population centers.

No so long ago the Aral Sea was the world's fourth largest inland sea, sustained in an arid region by water carried by two rivers originating in mountains far to the west: the Amu Darya River and the Syr Darya River. Yet the water in these rivers was diverted to irrigate the surrounding desert to grow rice, melons, and cotton. The global market demand for these agricultural products far exceeded that of the local fisheries. Consequently, the amount of water taken from these rivers doubled between 1960 and 2000.

The immediate effects of this water diversion were predicted and accepted in terms of economic gains. The sea's salinity quadrupled, the fisheries collapsed, and what remains of the lake is now brine-encrusted. In less than a lifetime, coastal towns supported by commercial fisheries have become abandoned desert salt flats and the formerly flourishing tourism industry has collapsed.

But the secondary consequences of this rapid ecosystem transition were not fully anticipated. The Aral's shrinkage has devastated the land around it. The drying of the sea has exposed almost 30,000 square kilometers of lake bed filled with salts, dried pesticides, and agricultural run-off. Each year, millions of tons of salt, sand, and dust are lifted from the lakebed by winds and carried aloft, wreaking havoc wherever they land, damaging plants, crops, and human health far beyond the sea itself.

The climate around the lake has also changed for the worse: air is drier, winters are colder and longer, and summers are hotter. The number of rainless days has risen from 30 to 35 in the 1950s to between 120 and 150 today.

has varied widely over geologic history, there is no analog for the suite of dramatic changes occurring around us now. Some in the scientific community have begun to refer to this current period in Earth's history as the *Anthropocene*, referring to the dominance of human impacts that are now so evident on Earth.

Today's rate of change suggests a far greater period of extinction is happening, one comparable to the mass extinctions that closed the Paleozoic and Mesozoic eras.

The late Pleistocene may be the Anthropocene's closest parallel period in Earth's history. Between about 50,000 years ago and 10,000 years ago many of the large mammals and large birds, and some of the large reptiles, went extinct. While we cannot ascribe precise roles to each of the direct and indirect causes of environmental change in the late Pleistocene, it was associated

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EVA HORNE, KONZA PRAIRIE BIOLOGICAL STATION.

with both climatic change and expansion of human influence over the environment—a combination which resulted in extinctions on a very short geologic time scale. Today's rate of change suggests a far greater period of extinction is happening, one comparable to the mass extinctions that closed the Paleozoic and Mesozoic[9] eras.

Earlier environmental catastrophes of similar scope largely impacted non-human species however human populations and societies have not been immune from collapse. Several examples from history demonstrate our own reliance on natural systems and apparent extinction at local scales. The magnitude of the present danger stems from two facts: current rates of environmental change exceed what modern society has experienced; and the billions of people now on the planet are highly interconnected through socioeconomic systems providing food, water, and energy. The global scale of the coupling of human and natural systems means the consequences of change are also global.

[9] The end of the Paleozoic is defined by the largest mass extinction in history; approximately 90% of all marine animal species went extinct. The end of the Mesozoic is defined by the extinction of land-bound dinosaurs and a diversification of flowering plants that lead to their domination of terrestrial vegetation.

Unfortunately, the adage "history repeats itself" does not strictly apply to complex environmental systems that evolve. Were it to be true, then it would be straightforward to estimate the magnitude of forcing factors responsible for past environmental change and use this information to predict the future. Instead, environmental processes are contingent on the starting conditions and these are never the same; the continents move, one life form replaces another, and chemical concentrations in the oceans and atmosphere adjust. For example, 55 million years ago Earth was as warm as the hottest predictions for the 22nd century and a methane release poisoned the atmosphere and oceans. Does that past scenario mean we should forecast a similar poisoning in the foreseeable future? The outcome of higher temperatures in the 22nd century may not resemble the past event. Contingency matters but we cannot yet separate the effects of contingency from the behavior of a complex system sufficiently to predict outcomes.

KENNETH LOHMANN, UNIVERSITY OF NORTH CAROLINA

SUE NICHOLS, MICHIGAN STATE UNIVERSITY

KYLE SUMMERS, EAST CAROLINA UNIVERSITY

RESEARCH PRIORITIES

New Strategies for a New Era

ATTEMPTS TO UNDERSTAND and model Earth's complex environmental systems must be greatly accelerated because these systems are changing rapidly; we face the threat of crossing tipping points that we might not be capable of reversing. These efforts must draw on a wider array of disciplines: biology, chemistry, geology, hydrology, ecology, and climatology in the natural sciences; economics, sociology, anthropology, geography, psychology, and political science in the social and behavioral sciences; and mathematics, statistics, computer and information science, engineering, energy and materials sciences, and technology. We can no longer use these science and engineering disciplines as tools in isolation from one another. To tackle global environmental challenges will require truly interdisciplinary approaches.

A hallmark of any strategy for interdisciplinary environmental research should be a focus on understanding the multi-scale integration of environmental systems in space and time and from individuals to collectives. We are now at a point where human actions are global in both scope and extent, creating a complex network of interactions wherein direct connections and feedbacks play out over a wide range of spatial scales. Issues that were previously addressed at a local level cannot be adequately understood without a regional and, increasingly, a global perspective. Crucial advances will come from integrating processes that operate at different scales—from local to regional to global scales, and understanding the long-term consequences of short-term activities.

If we are to understand and predict the consequences of climate change, land and water use change, and wholesale alteration of ecosystems, a framework different from the traditional approach offered by physical and natural science disciplines is needed. Efforts to advance our understanding of complex environmental problems require studying ecological and social systems holistically as a single coupled system. A research framework for enhanced collaboration among the biological, geophysical, and social sciences and engineering should address the issues of scaling and of thresholds and tipping points critical to our understanding of the long-term effects of environmental change. To accomplish this will require fundamental advances in the theory of complex systems and in the qualitative and quantitative analyses of complex system behavior. We must increase our ability to study how processes and outcomes connect across a broad range of spatial scales—from local to regional to global and of human dimension from individual to collectives. We also need to explore the role of contingencies in shaping dynamics of coupled natural-human systems to clarify the degree to which past outcomes of certain processes will be repeated in the future.

STEVE SILLETT, HUMBOLDT UNIVERSITY

The call for integration of natural and social science perspectives in research on environmental systems is not new; for example it was the theme of a previous report by the AC-ERE in 2005.[10] Many academic institutions have embraced this notion through the establishment of interdisciplinary programs and centers in environmental studies and sustainability. However a significant intellectual integration of social and natural sciences and engineering remains rare and support for such efforts is far too restricted. NSF, through its foundational support for all the science disciplines and engineering

[10] *Complex Environmental Systems: Pathways to the Future;* 2005.

USDA NRCS

JERRY TING

technologies, is in a unique position to promote such interdisciplinary research. But a far greater commitment is needed from all parts of NSF if we are to make the advancement in understanding of coupled human and natural systems that will be necessary to address global environmental challenges.

Thinking About the Whole—Not Just the Pieces

The call for more integrated approaches to address global environmental challenges goes beyond the traditional call for considering complicated processes that require an interdisciplinary approach and the appreciation of multiple causes and effects. Our environmental challenges are not merely consequences of complicated systems, but of complex adaptive systems.[11] Complex adaptive systems are dynamic systems whose components can adapt and change in response to the overall state of the system or to particular variables in the system. Coupled natural-human systems are complex adaptive systems. For example, commercial fishermen change their efforts in response to the perceived abundance of fish, the costs of fishing, wholesale prices, the nature of regulations, etc. Each of these variables affects the other and the dynamics of all create feedbacks among variables in many directions along with time lags in responses. This complexity creates non-linear behavior in the entire system in ways that are unexpected, contingent on prior events, and potentially irreversible. There is a pressing need to understand coupled natural-human systems in terms of properties such as resilience to perturbation and capacity to recover from disturbances. Given their inherent complexity, research should be directed at understanding how the components of coupled natural-human systems respond to one another so that we can begin to predict how the entire system behaves.

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[11] Simon A. Levin. 1999. *Fragile Dominion: Complexity and the Commons.* Perseus Publishing.

Systems analysis in environmental science and engineering has a distinguished history, from 1940s descriptions of lakes as systems of energy transfer[12] to 1990s mathematical analyses of ecosystem processes and biodiversity.[13] More recent efforts have sought to integrate these natural system models with models of human systems. The goal of these approaches is to identify and understand the interactions among the properties of a system as a whole. The value of systems analysis is that it lends itself to thinking holistically about the emergent properties of complex systems such as resilience. Systems analysis confronts the complexity of environmental systems by focusing on features such as feedback loops and thresholds for change, and provides a common framework that can transcend disciplinary boundaries and multiple scales of interaction.

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The need for holistic scholarship that identifies higher level system behaviors is especially evident in the arena of energy, the environment, and the economy. For decades the technical challenges of developing new energy sources have been investigated in near isolation from efforts to confront environmental challenges and human behavior. The view that these were competing enemies was to a large degree played out in the organization of research with institutional barriers among environmental research, energy technology research and social sciences research. Competition is intensifying over finite water supplies needed to support various energy technologies, ecosystems, and households. Biofuel production now competes with other land uses already stressed on a global scale to meet the needs for food, feed, fiber, and biodiversity. These should be sufficient proof that we place ourselves in peril if we do not simultaneously consider environmental and energy systems together with human behavior and socio-economic systems. In light of the rapid growth of the human population and improved living standards, we cannot solve energy supply needs nor identify policies that will maintain environmental quality without an integrated understanding of the coupled energy-environment-human behavior system.

Improving understanding of what might be called "the human component" in Earth's environmental systems will be a key factor in developing effective strategies.

Expansion of urban systems represents another striking example of the need for integrated whole system thinking. More than 80% the U.S. population resides in urban centers and that proportion continues to increase. Significantly more than half of the US population lives within 50 miles of the coast. The engineering of urban infrastructure has long lasting and global impacts on ecosystems that supply resources and assimilate wastes. A challenge is to understand the emergent properties of urban systems (e.g., economic structures, information flow, material and energy use, transportation patterns, urban health, heat island effects, land use and density,

[12] Lindeman, RL (1942) *The trophic-dynamic aspect of ecology.* Ecology 23:399-418.
[13] Loreau, M. (1998) *Biodiversity and ecosystem functioning: A mechanistic model.* Proc. Natl. Acad. Sci. Vol. 95, pp. 5632–5636.

air quality, local regional and global impacts of the resource demands and waste generation). In the words of Klaus Toepfer, Executive Director for the United Nations Environment Program, "the battle for sustainable development, for delivering a more environmentally stable, just and healthier world, is going to be largely won and lost in our cities."[14]

Environmental challenges, and the systems from which they emerge, span multiple political, jurisdictional, and natural systems boundaries. This can result in mismatches between the research data and the various stakeholders and policy makers unless efforts are taken to define system boundaries in a way that encompass the relevant human and natural system processes. Hence, an integrated system approach is not simply a method of analysis but a way of conceptualizing the issue from the beginning.

"Tragedy of the Commons" Becomes Collective Wisdom, If Choices are Enforced

Since the publication of Garrett Hardin's "The Tragedy of the Commons" in 1968, environmental researchers have tried to understand how humans operate in settings where resources are held in common. When the consequences of their actions do not immediately affect them, individuals might be expected to operate in different ways than when they are directly impacted. Research suggests that need not be the case if decision making includes local people and decisions are enforced.

Researchers have studied different strategies for restoring and managing forests in more than 60 sites in the Americas, Asia, and Africa. Forests were found to be effectively managed for ecosystem quality regardless of whether the property was privately owned, managed cooperatively, or publicly managed—if a collective decision about that management, once reached by residents of a city, town, or village, was enforced.

Forests were found to be effectively managed for ecosystem quality regardless of whether the property was privately owned, managed cooperatively, or publicly managed—if a collective decision about that management was enforced.

Research on marine reserves that protect marine ecosystems while ensuring the livelihoods of local people has yielded similar results. A variety of approaches have proven successful—if local residents are part of the process collectively developing strategies to manage reserves and the rules to which all parties have agreed are enforced.

These results also emphasize the need to consider differing perceptions and understandings of the relationship between humans and environment in studies of complex environmental systems. Perceptions are shaped by values, social norms and ideologies that together influence behavior, including

P. HOAGLAND, WHOI

[14] Quoted from Press Release: United Nations Environment Program #290

The Apalachicola-Chattahoochee-Flint Drainage Basin

For almost two decades Florida, Georgia, and Alabama have been engaged in a legal battle over water. At the heart of the debate is one of six high biodiversity areas in the U.S., the Apalachicola-Chattahoochee-Flint Drainage Basin. The basin harbors a high concentration of threatened and endangered species within its 50,000 square kilometers of rivers and streams in eastern Alabama and western Georgia including urban Atlanta. The water in this basin ultimately drains to the Gulf of Mexico, 500 kilometers to the south, from the mouth of the Apalachicola River in Florida's panhandle.

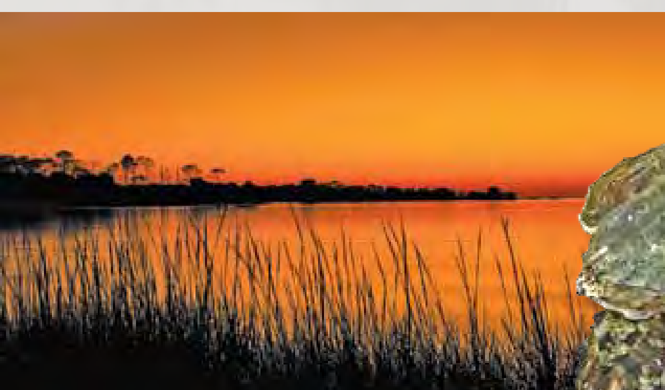
Increased urban development in Georgia has led to increased and conflicting demands for surface water in the upper basin, decreasing the flow through the system. Increased groundwater withdrawals for irrigated agriculture combined with persistent droughts have resulted in lower flows in the lower basin.

The effect on the downstream oyster industry has been severe, an industry that comprises 90 percent of Florida's oyster harvest and 10 percent of the oyster harvest nationwide. As freshwater input has declined, oyster populations have suffered from increased disease and predation in the increasingly saline estuaries. As the traditional oyster fishery becomes less profitable, other fisheries face increased harvest pressure to compensate for the economic loss from oysters. The economic foundation of the lower river region has shifted dramatically.

PFLY

Is surface water throughout the basin sufficient to support vibrant economies and maintain critical flows to support aquatic species, and groundwater in the lower basin to support critical habitat downstream?

Similar problems of connected environmental and social systems that share resources are faced everywhere. A systems approach to sustainable policy and management of the Apalachicola drainage basin requires that water flow in the river system be viewed within both the watershed and estuarine ecosystem context, with local conversions of water availability into economic value being balanced with both direct and indirect consequences to the natural resources and entire system functioning and services. This approach necessitates a holistic, social, economic and environmental systems perspective.



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PENELOPE FIRTH, NSF

cooperative behaviors critical to managing environmental systems. Value systems are themselves partially shaped by social and environmental interactions. Variability in cultural value systems, social norms, livelihoods, governance, and human behaviors is the foundation upon which coupled natural-human systems must be understood.

Tipping Points in Complex Environmental Systems

Understanding cause-and-effect relationships within complex systems, such as Earth's environmental systems, is a difficult task. Simple models of system interactions view one variable's response to another as straightforward, much as you expect that the sound from a radio will increase as one gradually turned up the volume knob. But complex systems can instead display "non-linear" or "abrupt" behavior with changes in one variable seeming to have no direct influence on another until a crucial threshold is reached. Then the second variable in turn responds with a dramatic shift in its character. Imagine the radio volume remaining steady even as the volume knob is turned up, until a critical threshold is reached and the speaker suddenly starts blaring loudly. Such thresholds, beyond which a system is dramatically altered, are referred to as tipping points.

The notion of tipping points[15] has become broadly accepted in the social and natural sciences and engineering although it is used in various ways. Here we refer simply to the occurrence of a critical threshold at which even a small stress or perturbation can result in an abrupt shift in the state of a system or in its dynamics. Tipping points are generally associated with major qualitative changes

RAMON ARROWSMITH, ARIZONA STATE UNIVERSITY

in system state or rate of change. Water that is gradually chilled still behaves like water (only colder) until a critical (freezing) point is reached and then it suddenly turns into solid ice. Unfortunately, tipping points in social systems or in complex environmental systems are not as predictable or as reversible as ice formation.

As we have become more aware of the connections among environmental processes, so we have become more aware of the potential to reach tipping points in many of Earth's systems; e.g., accelerated warming of the arctic due to changes in albedo caused by loss of snow cover is expected to cause rapid and wholesale change in the northern terrestrial ecosystems. Yet our understanding of Earth's systems and their coupling to social systems is inadequate to place confidence bounds on the likelihood of tipping points, or the magnitude of change that will occur. Our knowledge of tipping points in human systems is equally poor. Recent history provides examples of abrupt changes that can occur in financial markets or in social acceptance of individual behaviors. What factors lead to systemic and rapid behavioral change; at what point does cultural perception tip into awareness and then action?

The large uncertainty associated with tipping points, combined with the risk that

[15] Malcolm Gladwell. 2000. *The Tipping Point: How Little Things Can Make a Big Difference.* Little, Brown and Company.

From the Corn Belt to the Gulf of Mexico's "Dead Zone"

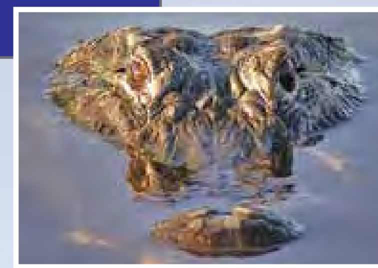
In spring and summer in the northwestern Gulf of Mexico, where the Mississippi and Atchafalaya rivers meet, appears a vast swath of water known as a "dead zone." The Gulf's dead zone is the second largest of the world's nearly four hundred documented human-caused coastal dead zones. All are areas with little to no oxygen in their sediments and bottom waters and, as a result, no crustaceans or fish.

The dead zone in the Gulf of Mexico was first noticed in the early 1970s. It has grown from an area of about 8,000 square kilometers when first systematically measured in 1985 to more than 20,000 square kilometers. Dead zones appear when phytoplankton production is increased beyond the point at which it can be consumed through the food chain. Dead cells sink to the bottom and are decomposed in the sediments by aerobic bacteria, and the activity of these bacteria depletes the oxygen from the sediments and bottom waters. The bottom waters remain depleted in oxygen when there is a stratified, or layered, water column preventing the mixing of oxygen in the surface waters to the bottom.

Environmental studies indicate the Gulf of Mexico's oxygen depleted waters began to appear seasonally

NANCY N. RABALAIS, LOUISIANA UNIVERSITIES MARINE CONSORTIUM

OMNISTUDIO



USGS

after intense farming and fertilizer use in the Mississippi River's watershed started post World War II and accelerated in the 1960s. Land use changes and farming practices, such as liming and changes in drainage and crop type and rotation, have increased water flow and changed water chemistry in the river. The net result has been a large increase in nutrients, primarily nitrogen, delivered to the Gulf. The same sequence of events is documented worldwide with the increased delivery of nutrients (agricultural, wastewater, atmospheric) stimulating phytoplankton growth.

And this process may be accelerating due to seemingly unrelated policies to address the nation's energy demands. In an effort to meet the Renewable Fuel Standard goals for biofuel production as specified in the Energy Independence and Security Act of 2007, farmers are rewarded for increased corn production used to make ethanol. As a consequence, lands previously set aside for conservation or in production for other crops may be shifted into corn production with an expected increase in levels of fertilization. Greater nitrogen inputs on lands in the Midwestern U.S. will result in increased export of nitrogen to the Gulf of Mexico.

Energy security motivates a national policy that shifts land use decisions by farmers whose collective action affects a coastal ecosystem and threatens economic security of a fishing industry located thousands of kilometers away. This illustrates the long-distance connections of environmental, energy, and social systems.

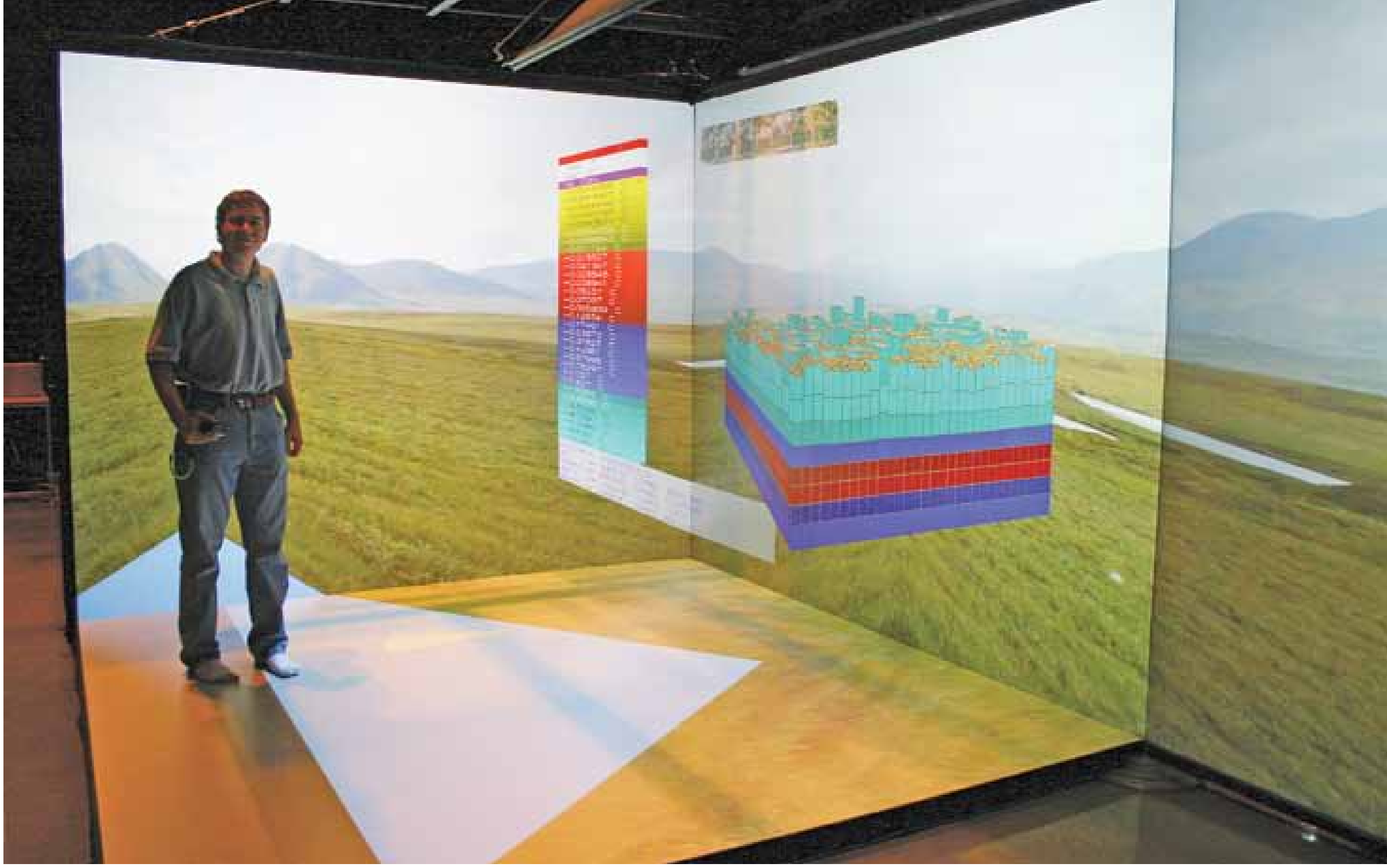
PUBLIC DOMAIN

they bring about drastic change, suggests that they can be viewed as low probability—high consequence events, as in the hazard literature. From that perspective, a research priority is to recognize early warnings, define boundaries of potential impact (scenarios), and develop mitigation plans. Alternatively, tipping points can be viewed as a consequence of deterministic processes, i.e., alternate system states, as in the ecological literature. These two perspectives are neither mutually exclusive nor exhaustive. They do, however, illustrate why long-term and comparative studies are important in developing a means to anticipate tipping points in environmental systems. Long-term studies provide baselines in rates of change; comparative studies help define boundaries of likely change or alternate states that the system may assume if pushed past a tipping point. Such studies are especially crucial in the context of coupled natural-human systems where the consequences of a tipping point reached in one system may cascade across systems.

JOHN HOBBIE, MARINE BIOLOGICAL LABORATORY

Without a vastly improved understanding of tipping points, we will remain unable to forecast the likelihood of disruptive abrupt changes, and we will remain ill prepared to mitigate their impacts.

Developing a predictive understanding of tipping points and abrupt change in environmental systems represents a major intellectual challenge, but it is one that we must undertake. The scale and complexity of the processes are great; human behaviors impact regional and global scale processes in ways we have only recently recognized. The feedback of those changes on human systems is even more poorly studied. Further, these systems are dynamic, undergoing continuous changes that alter the nature of connections and make them unpredictable in their outcome. Hence we can't simply look to the past to predict the future. Without a vastly improved understanding of tipping points, we will remain unable to forecast the likelihood of disruptive abrupt changes, and we will remain ill prepared to mitigate their impacts.


LEONE THIERMAN, ARCTIC REGION SUPERCOMPUTING CENTER, UNIVERSITY OF ALASKA, FAIRBANKS

To address this scientific challenge will require a major investment in integrated research on complex environmental systems. We need to be able to foresee the conditions under which, and the time when, major changes in environmental systems will occur and further predict future scenarios. Can we identify vulnerabilities to threshold change, i.e. leverage points in the dynamics of systems that make them especially sensitive to perturbations? Can we identify the processes that lead to either positive or negative feedbacks to perturbations? Can we stop movement toward a tipping point? Can we reverse a system's trajectory once a tipping point is reached? How can we mitigate the changes that we expect to occur? A tipping point may not equate to a "point of no return" but it may mark a new state in which environments and humans interact differently. How can we adapt to the new state that is reached after a tipping point? These are all questions that motivate fundamental environmental research. These are questions to which society will need answers in the near future.

Promoting Integrated Science and Engineering to Tackle Environmental Challenges

Recognition is growing within academia, and government, far beyond land grant institutions and engineering colleges, of the need for fundamental research directed at solving real problems facing society.[16] An example is the emerging field of sustainability science, an interdisciplinary approach to understanding the complex interaction of social and natural sciences. This shift towards needs-driven research that improves the human condition should be embraced by NSF, especially since it is clear that addressing the science and engineering questions will require fundamentally new discoveries and synthesis.

NSF is uniquely positioned to provide leadership in this endeavor. Among the five

[16] J.P. Holdren. *Science and Technology for Sustainable Well Being.* Science (25 January, 2008) 319: 424-434.

JUPITER

Bluer than Blue: Tipping Point for Glacier Melt

Beautiful they are, but their beauty is only skin deep. Saucer-shaped lakes have formed like blue pockmarks on snow-white glaciers in Greenland, betraying an accelerating melting of the ice cap there.

Greenland's ice cap is the largest in the Northern Hemisphere and second largest in the world after the Antarctic ice sheet. Should the Greenland ice cap melt, the world's oceans would rise by several meters and coastal cities would be flooded.

Climatologist Jason Box of Ohio State University has found that meltwater accumulating in Greenland's "super-blue lakes" drains through the ice sheet to the bedrock below. The meltwater seeps through moulins, vertical shafts or cavities in a glacier, where it accelerates melting of the glacier and may act to allow the glacier to slide more easily over the bedrock below, speeding its movement to the sea.

"That melting is happening where we can't see it, though," said Box, "along the glacier's underside. Two of us were out in a small rowboat on one of the lakes," he remembers, "when we were literally sucked into a melt-river rushing into a moulin. It took everything we had not to get swept along with the fast-running water and end up at the bottom, underneath the world's second largest glacier."

The water running through Greenland's moulins is incredibly powerful, which tells you something about how fast the melting is happening: once it reaches a certain critical point, it becomes a torrent. The nonlinear nature of this process suggests a possible tipping point that, once reached, results in a sudden greatly accelerated movement of glacial ice to the ocean.

The problem is no one yet knows exactly where that crucial point is. ■

research investment priorities outlined in the NSF Strategic Plan is "Foster research that improves our ability to live sustainably on Earth." Among all the federal agencies NSF alone supports all the relevant science and engineering disciplines, including the mathematics, computer, and social sciences, necessary to advance our understanding of complex environmental systems. In addition, NSF has long valued interdisciplinary research and has recently linked that value to the notion of transformational ideas.[17] Promoting transformational, multidisciplinary research is another investment priority in the NSF Strategic Plan. In recognition that major advances often emerge at the edges and interfaces of disciplines, NSF has placed a high priority on interdisciplinary research training through its IGERT (Integrative Graduate Education Research Traineeship) grants for graduate student training.

The nation must make a far greater investment in interdisciplinary environmental research if we hope to meet the challenges that confront us.

But it is not enough to instill in individual researchers or teams of researchers the value of reaching across disciplinary boundaries, redefining their approaches, and addressing broader scale questions. If NSF is to be an agent of change in environmental research, high priority must be given to the allocation of funds to broadly interdisciplinary research on complex environmental systems. NSF's Biocomplexity in the Environment (BE) priority area was instrumental in stimulating collaborative, team-oriented, interdisciplinary

[17] NSF working group on Facilitating Transformative and Interdisciplinary Research http://www.nsf.gov/nsb/meetings/2008/0922/minutes.pdf

Changing States: Social System Resilience and Recovery

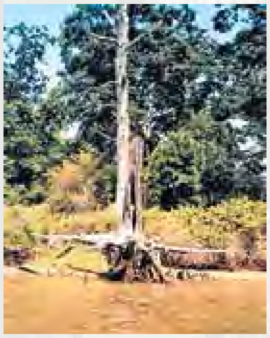
The whole world watched as the Gulf Coast drowned in the aftermath of Hurricane Katrina in 2005. Graphic images portrayed thousands of people in dire need and the tremendous physical devastation inflicted on the region's natural and built environments. Hundreds of thousands of hectares of land were pummeled and economic losses exceeded $125 billion for the hundreds of thousands of homes, buildings, bridges, vehicles, ships, and other infrastructure elements destroyed. The human toll was horrific; more than 1,800 people lost their lives and an estimated 450,000 people were displaced for weeks, months, or even permanently. The social system and the infrastructure needed to support its recovery were devastated.

While it was immediately obvious that New Orleans had been stressed in dramatic ways as result of a single yet massive disturbance, only later did we question whether the system had been pushed past a point of no return. While the city and region will undoubtedly recover in many ways, it is unlikely to ever be the same. Katrina cut the threads of the city's social fabric and it unraveled.


DHS


NOAA

Entire groups of the society were dislocated, greater than 100,000 people, a quarter of the pre-hurricane population, are still missing from the city's census rolls. Public and private infrastructure and services have been slashed.


MARY HOLLINGER, NODC BIOLOGIST, NOAA

How did this happen? In the years since Hurricane Katrina struck the Gulf coast, scientists and engineers have examined largely disciplinary components of the storm and its aftermath from levee failures and ecosystem damage to weather predictions and human responses in the midst of catastrophe. But the question can be more comprehensively asked: How was a social system, situated in a highly-developed, economically robust, and politically powerful country, brought to its knees by flooding from a hurricane?

We understand that coupled natural-human systems can change in unexpected ways when stressed and, as exemplified by Katrina, there are a myriad of social considerations intimately coupled to natural environmental systems. In the face of this complexity and uncertainty, research should be directed at understanding the responses of complex systems to disturbance, especially properties such as resilience and rates of recovery.

PENELOPE FIRTH, NSF

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research. But the BE initiative was short-lived and few funding opportunities now exist within the foundation for broadly interdisciplinary environmental research. The picture is similarly bleak from the broader perspective of all federal funding for environmental research; it has been flat since the early 1990's and even declined in recent years.[18] The nation must make a far greater investment in interdisciplinary environmental research if we hope to meet the challenges that confront us.

NSF must find more lasting ways of promoting broadly interdisciplinary research across the life and physical sciences, engineering, and social and economic sciences. The call for more interdisciplinary and system approaches to real world problems echoes from many quarters, including a study by the National Academy of Sciences[19] that also reviewed barriers to interdisciplinary research and education within both academia and funding organizations. A recent report by the National Science Board[20] calls for strengthening "interdisciplinary systems approaches" for research programs in the natural and social sciences in order

[18] AAAS federal budget historic trends by discipline: http://www.aaas.org/spp/rd/guidisc.htm

[19] *Facilitating Interdisciplinary Research*. 2004. The National Academies Press, Washington, D.C. http://www.nap.edu/catalog.php?record_id=11153

[20] *Building a Sustainable Energy Future: U.S. Actions for an Effective Energy Economy Transformation*. National Science Board of the National Science Foundation, NSB-09-55, August 3, 2009.

to advance the nation's development of a sustainable energy economy. There is likely much to be learned about the practicalities of fostering collaborations and evaluating proposals for interdisciplinary projects. For example, are there limits to the scaleability of interdisciplinary research questions and the structure of research teams? To achieve a transition to greater interdisciplinary innovation in the research community, NSF needs to itself become more innovative in how it reviews and supports such research.

In light of broad agreement on the value of interdisciplinary research, we ask why interdisciplinary environmental funding programs are not a higher priority? The Committee believes that the seriousness and urgency of the environmental challenges before us require a major investment in this area. This need not be borne by NSF alone. Funding from NSF could be leveraged in partnership with other agencies to allow better integration of the basic and applied research. However, the breadth of NSF's research mandate is critical in bringing the interdisciplinary expertise to bear on the complex problem we have outlined.

We urge NSF to develop and sustain broadly interdisciplinary (e.g., cross-directorate) programs that encompass the dynamic relationship between humans and the environment. The most prominent example of such a program is the Dynamics of Coupled Natural and Human Systems, a multi-directorate funding opportunity. More such cross-directorate activities should be developed. NSF presently invests nearly a sixth of its annual budget in environmental research and education; however, little of that goes to cross directorate research programs. It is equally important that NSF provide a longevity to interdisciplinary programs that is

EVA HORNE, KONZA PRAIRIE BIOLOGICAL STATION

similar to "core" disciplinary programs within directorates. Longevity of programs is critical to encouraging scientists—especially for those early in their careers—to develop and commit to the collaborations necessary to undertake interdisciplinary research projects.

Several conceptual frameworks have been proposed to reflect the nature of natural-human system interactions. One general approach is to consider drivers and feedbacks that affect physical and biological processes as one system, and drivers and feedbacks that affect human behavior and institutions as a distinct system, with ecosystem services as the coupling link between the two systems. A focus on ecosystem services was the central approach taken by the Millennium Ecosystem Assessment,[21] which defined various categories of ecosystem services. The Long-Term Ecological Research (LTER) community has also advocated for this framework to guide future investments in long-term environmental research in its Integrative Science for Society and the Environment initiative.[22] Alterations in the availability of ecosystems services, such

[21] Millennium Ecosystem Reports, http://www.millenniumassessment.org/en/index.aspx
[22] http://www.lternet.edu/decadalplan/

as water purification or food production, can engender changes in human behavior and institutions that feed back to the ecosystem processes providing that service. For many ecosystem services, such as fisheries, human institutions have been created specifically to insure sustainability of the services.

NSF needs to broadly support efforts to conceptually unite the social and natural

USDA ARS IMAGE GALLERY

sciences. This includes considerations of economy and valuation systems to encompass services from natural systems. But it also includes the broad interface between human perception, behavior, values, and decision making, and human-built systems. It is important to recognize that for most people the immediate environment is an engineered (urban) system and information moves globally through cyber-networks. Engineering, computer and information science and technology must be explicit considerations of any framework for coupled natural-human systems. This includes developing the cyberinfrastructure to gather information, model, and visualize the emergent properties of urban systems.

Be it people-to-people, people-to-machine, and/or machine-to-machine, sensor networks allow researchers to detect and approach scientific challenges in new and creative ways.

Networks for Environmental Research

New technologies have allowed for scientific exploration on broader temporal and spatial scales. The development of sensor networks is akin to stretching a "cyber skin" across the planet, providing ubiquitous, autonomous, and faster telemetry and monitoring capabilities than ever before. Be it people-to-people, people-to-machine, and/or machine-to-machine, sensor networks allow researchers to detect and approach scientific challenges in new and creative ways.

A growing awareness of the need for a better understanding of the full range of complex environmental system dynamics has spurred the development of long-term observational networks. Among existing, new, or proposed NSF-supported networks are: the Network for Earthquake Engineering Simulation (NEES); the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC); LTER; NEON; EarthScope; OOI; AON and WATERS. These complement the environmental observing investments of other federal agencies such as NASA satellites and NOAA and USGS networks for climate and hydrology.

These major infrastructure investments attempt to address the need for environmental observations and experiments on multiple processes at all spatial and temporal scales. They fill an important gap in the science goal of linking local, regional, and global scale processes. The promise of these networks is powerful, allowing environmental scientists to ask and answer questions at larger and more complex scales than previously possible. NSF

GINNY L. ECKERT, UNIVERSITY OF ALASKA

must lead to ensure the design of well-integrated networks that advance the fundamental research needs of the environmental sciences. It is also important that these observing systems be well-coordinated with those of other agencies and governments to ensure interoperable software and data bases.

Associated with environmental networks is a need for modern data repositories and archives that allow the most effective and efficient capture and integration possible of data from different networks and all researchers.

MARCOS GUERRA

The issue of long-term data storage and access goes beyond the establishment of new environmental observatories. To facilitate greater synthesis and multi-disciplinary approaches, it is essential that all data collected in environmental research—from local to global scales—be made easily accessible. NSF must move beyond an expectation of data sharing and should require that plans for data management and sharing be considered in all research proposals, and that funding to implement these plans be included in all awards. Shared databases are especially important to promoting synthesis across disciplinary boundaries.

How we manage a constant flow of data in real time is essential to the effectiveness and adaptive management of environmental observatories and research activities they support.

The development of cyberinfrastructure, and continued research in computer and information science at the interface of the life, physical, and social sciences and engineering, are integral to the success of all environmental networks and data management schemes.[23] Data for modeling, predictions, and forecasting are essential to mitigating the effects of accelerated and abrupt changes. The explosion of real-time data availability calls for near real-time analysis and distribution if those data are to be most useful, especially in saving lives during hurricanes or earthquakes, or predicting likely outbreaks of infectious diseases. How we manage a constant flow

[23] Complex Environmental Systems: Pathways to the Future, NSF Advisory Committee for Environmental Research and Education, March 2005

of data in real time is essential to the effectiveness and adaptive management of environmental observatories and research activities they support.

A major challenge is the need for effective integration of observations of human activity and behavior into environmental observatory networks, for example integrating satellite-based observations of land use with data on other forms of human activity. On their own, environmental observations detect changes in the natural system but fail to provide critical information on the human processes that drive such changes, such as employment and recreational opportunities driving development and settlement patterns. The realization of the growing need for social and behavioral science research on human systems that is integrated with research on natural systems has spurred a need to develop observational networks on human activity. Such networks can provide better data to test hypotheses relating human actions to natural system changes, as well as human responses to changing natural conditions. The development of regional monitoring networks would be extremely beneficial in developing new insights into vulnerability and resilience of coupled systems. Such networks could help us understand, for example, how, when and where recovery after natural disasters takes place and what processes foster or hinder such recovery, leading to better models whose predictions can be used for future events. There already exist data about human behavior, for example via cell phones activity and Google searches, but the science and ethics of integration of data like these into the environmental system analysis lags.

A History of Change in Coupled Natural-Human Systems


MIKE WEBER, UCSD-TV

The western Great Plains and the Front Range of the Rocky Mountains of Colorado include the mountains east of the continental divide, down through the foothills and eastward through the prairie. The region is vast and includes the urban centers of Pueblo, Colorado Springs, Denver, Boulder, Estes Park, Greeley, and Ft. Collins. Two ecological research sites (LTER—Niwot Ridge on the Front Range; Shortgrass Steppe on the Western Central Plains) provide a multi-decade record of environmental change in this region, shaped by numerous anthropogenic disturbances and the conflicts between property rights, conservation efforts, and public policy.

Native Americans were all but extirpated from the region in the 19th century. The landscape became a patchwork of private and federal land open to cattle grazing and agriculture. In the early part of the 20th century, the prairie region was hard hit by the drought and dust bowl in the 1930's. This promoted changes in land use away from till agriculture and modifications in grazing. During the 1930's and 1940's, one of the largest federally sponsored water projects diverted water from the Rocky Mountains western slope to the Front Range. In recent decades the region has experienced an explosion in population growth, but an extended drought has now strained water reserves and, to some extent, has curbed development. The fire danger was so severe during the summer of 2002 that Colorado imposed bans on open fires and restricted public access to many forested areas.

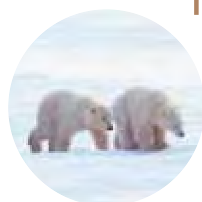
These transitions in land use and water allocation, from agriculture to urban and suburban, have accompanied human population growth and are coupled with the natural drought cycle of the region. As a whole, they have significantly altered air quality, regional climate, plant communities, soils, and the distribution of wildlife. In the face of climate change, this region is likely to experience even greater changes. Forecasting this future will require broader scales of environmental observations and research that link regional and global change processes.

ENVIRONMENTAL LITERACY

Moving Beyond Changing Light Bulbs

ALTHOUGH IT IS NOT easy to appreciate the complexity of coupled systems, citizen appreciation for even the basic environmental science concepts is not what it ought to be. Current assessments of environmental literacy from formal education settings indicate we have challenges ahead in fostering an understanding of environmental science and its use in decision-making by the public. Participation rates in environmental science and education fields do not reflect the demographics of society as a whole. A uniform agreement on what constitutes environmental literacy, including the learning progressions that lead to it, is lacking in the larger education and scientific communities.

Similar challenges exist in informal learning settings where we must find innovative ways to actively engage citizens in new ways of understanding the Earth on which we live. An effort addressing citizen education and engagement in environmental science is of immediate importance. When someone can see for themselves the effects of global warming on, say, their garden, the songbirds visiting their birdfeeders, neighborhood snowfall amounts, or severity of summer thunderstorms, it enhances their environmental literacy and better informs their behavior. The potential of linking cyber-connected global environmental monitoring systems with cyber-connected citizen science networks also offers a level of participation never before possible. NSF should identify and act on ways of using growing computer literacy and technological advances to foster environmental literacy.



CLAUDIA ZAN, CORNELL LAB OF ORNITHOLOGY

An Environmental Literacy Framework: Learning What We Need to Learn

The nation needs a framework for environmental education that integrates disciplines and encourages a holistic perspective of Earth's environmental systems. To address the planet's complex environmental challenges we need to develop a new environmental literacy framework. Environmental science is interdisciplinary and our education system should reflect this. Rather than recommending another set of education standards to compete with existing standards[24] we propose the development of a unified framework showing paths through a traditional programs or curricula that would lead to greater levels of environmental literacy.

The development of such an environmental literacy framework requires that concepts important to creating an environmentally literate public be identified and that the increasingly sophisticated ways of understanding these concepts, or learning progressions, be researched and implemented. Implementing the framework in formal education settings would necessitate greater coordination of the curricula to align core concepts with results of research on learning progressions. The framework should bridge the gap between the academics who do the research, the tool developers who design the curricula and applications, and the communicators and educators who translate complicated environmental science into broadly understandable terms.

[24] National Science Education Standards, Technological Literacy Standards, and currently developing Engineering Education Standards and Climate Literacy standards.

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Significant pedagogical questions for research should be part of this ambitious agenda: What is environmental literacy and how do we define it? How will we know if we are succeeding? How do we build a variety of educational experiences—in school and out—for all ages and differing levels of basic understanding? How do learners of all ages come to understand science as a process, one that constantly changes as our models and understanding advance? What methods, ideas and tools promote interactive and participatory environments for learning, especially those that take advantage of real (and real-time) scientific data? How do we move public interest in the environment beyond enthusiasts and professionals and into the mainstream of society? How can we better understand the potential of new visualization tools for science learning and environmental literacy? What are promising ways of combining environmental science and cyber-learning?

We ask NSF to support interdisciplinary efforts that develop and promote the pedagogical approaches needed to attain environmental literacy. This activity should be supported jointly by all NSF directorates in partnership with the Education and Human Resources Directorate, and include K-12, higher education, and informal and adult learning environments. Below we outline particular challenges for formal and informal environmental education.

Formal Environmental Education

A large fraction of our environmental future depends on the ability of today's schoolchildren to understand and evaluate evidence-based arguments about the environmental consequences of human actions and technologies, and to make informed decisions based on those arguments. Preparing our children to be both aware and active at local-to-global scales places new demands on scientific communities even as our research knowledge base remains incomplete. Preparing our citizens also places new demands on our universities, schools, and teachers. Today's teachers are likely to have studied science, technology, engineering, and mathematics (STEM) as isolated topics as opposed to a systems-based approach in which the full breadth and complexity of all STEM disciplines affect the outcome. Pre-service and in-service teacher education and professional development must reflect the interdisciplinary nature of environmental issues.

As an educational outcome, the nation needs a workforce that can create the knowledge, technology, community, governance, and economy that improves well being in a fashion that is sustainable and robust.

We believe that an environmental literacy framework can build from a core of disciplinary concepts through interdisciplinary perspectives so students can build an increasingly sophisticated understanding of Earth's environmental systems. These efforts will require a rethinking of our current professional development models in the K-12 and higher education realms and of the interactions between K-12, higher education, and STEM research communities. New teacher development efforts are needed to increase K-12 teachers' content knowledge and to build on an understanding of the learning progressions of this knowledge.

As an educational outcome, the nation needs a workforce that can create the knowledge, technology, community, governance, and economy that improves well being in a fashion that is sustainable and robust. The complexity of the challenges we face demands a fundamental environmental literacy of all citizens that embraces the realities of diverse cultural perspectives, trans-generational time frames, and local to global connectedness. Our educational system must instill understanding of the world as coupled natural and human systems involving complicated, multi-scale interactions and having the potential for complex behaviors such as tipping points. The scope of these efforts should be wide and inclusive of attracting a diverse mixture of young people to interdisciplinary

NORTHERN VIRGINIA COMMUNITY COLLEGE

NPS/ERIC LEONARD

careers and of life-long learning for all. The educational tools and approaches we have used in the past are not appropriate: a K-12 system that leads to stove-piped disciplines and undergraduate majors.

Working toward this goal, NSF and other agencies have developed several related programs such as GK-12, Discovery Research K-12, and Math and Science Partnerships. Expanding successful models emerging from these programs would be an integral part of the framework.

Informal Environmental Education

An immediate impact in environmental literacy can be realized through informal science education. Already many organizations and informal science education institutions, including natural history museums, zoos, aquaria, and nature and science centers, are dedicated to environmental education. These efforts can be greatly expanded by web-based communication, which offers the potential to reach a large and more international public audience.

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Telecommunications have come a long way since an Earth-bound audience was connected to the Apollo 7 crew during the first live TV broadcasts from a manned spacecraft in 1968. Polar scientists regularly send research dispatches from Antarctica and the Arctic to school children all over the world. One can witness the largest gathering of cranes on Earth, live from the Platte River to their desktop 24/7 for six weeks straight, bandwidth permitting.[25] Of special interest are developments in media and telecommunications with potential application

[25] From late February to early April, National Geographic's Crane Cam (http://video.nationalgeographic.com/video/cranecam/) streams non-stop live video of the half-million migrating sandhill cranes resting in the Platte River Valley, Nebraska, on their way to their Arctic breeding grounds. An interactive website, online forums, and teacher instructional tools all provide hands-, ears-, and eyes-on activities based on the largest gathering of cranes in the world.

MINNESOTA ZOO AND EDUWEB

to environmental literacy, ranging from sophisticated geographically-based mapping software like Google Earth to online games and simulation activities. For example Wolf Quest,[26] an NSF-funded project by the Minnesota Zoo and Eduweb, is an online, multi-player, interactive, 3-D simulation game that teaches wolf behavior and ecology of Yellowstone National Park through role playing and intense social interactions.

Science as a public activity is well-developed in places like Europe, where experiments are underway to involve citizens in current scientific debates. These interactions happen in cafes and bars, universities and museums, and in virtual forums online. Evaluation of these activities shows that views and levels of understanding grow in these learning environments.

This fast-paced technological era provides exciting opportunities to all of NSF's Directorates and Offices, inviting much needed collaboration to accelerate the development of various tools and media that may advance environmental literacy. NSF should sponsor reviews of these models of engagement and promote experiments on how to adopt these and related innovations in the U.S. Ready to leverage is the existing large and enthusiastic community of media specialists, tool developers, instructional designers and communicators already bridging this gulf between environmental science and the public.

[26] www.WolfQuest.org

ENGAGING THE "CITIZEN SCIENTIST" IN ENVIRONMENTAL RESEARCH

THE COMPLEXITY OF environmental challenges demands that we all—the scientific community, decision-makers, and the public—participate in finding and implementing solutions leading to long-term environmental sustainability.

To successfully pursue an environmental agenda, the public must be actively engaged by the scientific research establishment in many different aspects of their work.

For the public, the concept of scientific literacy has moved beyond simply understanding science. To successfully pursue an environmental agenda, the public must be actively engaged by the scientific research establishment in many different aspects of their work. In other words, the "citizen scientist" should play an increasingly critical role in the scientific endeavor. A growing awareness of the human and equipment resource limitations by the scientific community, coupled with innovative programs and cyber-connectivity, has provided an unprecedented opportunity to expand worldwide citizen-scientist networks far beyond the reach of nascent efforts such as the Audubon Society's "Christmas Bird Count"[27] from a century ago. Examples of public participation in organized campaigns such as Feeder Watch,[28] The Global Learning and Observations to Benefit the Environment (GLOBE) Program,[29] and Project Budburst[30] show that the scientific community can connect the public to the scientific enterprise like never before.

In addition, citizen engagement initiatives such as The Lost Ladybug Project[31] show growing reciprocity in the nature of the public-science partnership. Direct organized responses to research results and the collection of data from citizen networks in turn influence future research. Citizen scientists more and more are participating in, and contributing to, the grand endeavor of better understanding our planet.

Involving the public in the process of scientific investigation, i.e., the collection and interpretation of data, should not be relied upon as a substitute for critical environmental observatories or research programs. There are serious issues of quality assurance and control to consider when data is collected by many different people with variable backgrounds of training and motivation. However, citizen scientists represent one component of engaging the public in science, and in the right situations can provide an incredible opportunity to complement by extension in space and time, a more rigorous but limited research program. Citizen scientists also provide a means to broaden the impact of basic research by extension and application, helping to bridge the gap between basic and applied research.

Ensuring that sound data management and accessibility plans are in place also will further the goal of engaging the public as participants in environmental science. Rather than focusing solely on scholarly presentations and publications, researchers need to work on their own

27 http://www.audubon.org/bird/cbc/history.html
28 http://www.birds.cornell.edu/pfw/
29 http://www.globe.gov/
30 www.windows.ucar.edu/citizen_science/budburst/

31 http://hosts.cce.cornell.edu/ladybeetles/ The Lost Ladybug Project is a nationwide hunt for ladybugs, funded by a $2 million NSF award to Cornell University. The project is intended to help scientists better understand why some species of ladybugs have become extremely rare while other species have greatly increased both their numbers and range. Species previously thought to have disappeared from former ranges have been collected by citizen scientists in neighborhoods across the country.

CAGAN SEKERCIOGLU

DUSTIN HAMPTON, DECISION CENTER FOR A DESERT CITY, ARIZONA STATE UNIVERSITY

or in collaboration with others to make presentations before trade groups, publish in periodicals aimed at a wider audience than the scientific community, and engage in other forms of outreach. Often, this means placing disciplinary research findings within the broader context of whole integrated systems. When members of the public can see the data behind scientific findings, including their contributions in the case of citizen scientist involvement, they are more apt to trust interpretations.

Engaging the public also means engaging decision-makers at all levels. People will not rely on scientific information if they don't understand it, or they question the motivation or integrity of the research methods that were used to generate it. Research on the ways people and organizations perceive and form attitudes about environmental change, how decision-makers might better deal with uncertainty, and how the interplay of different individuals and groups affects the management of Earth's resources, is critical. The results will help scientists become more effective in working with decision-makers—from households to small businesses to corporations to public servants—on environmental challenges.

Scientists and engineers need to become more aware of the roles they can personally play in making research more accessible and useful for decision-makers of all kinds. For more than a decade, the National Science Foundation has used both intellectual merit and broader impacts as review criteria to evaluate the significance of the proposed projects it is asked to support. Investigators should be encouraged to take more responsibility for conveying their findings directly to those people and groups who can use their insights and information. This means making research data and metadata accessible and interpretable with respect to their implications for policy or management decisions.

There is a critical need for policy-makers to better understand the interconnectedness of complex environmental systems, the feedbacks of altered environmental systems on human systems, and an appreciation for scaling issues and tipping points. Tools (i.e. visualizing scientific findings through GIS, video animations, games, simulations and other visual analytics[32]) must be developed to visualize and synthesize data from multiple sources and to simulate different policy scenarios. We call for the advancement of decision support tools that integrate knowledge across disciplines to address long-term consequences. Policy-makers and the general public must be engaged in activities that lead to a better understanding of the complex nature of environmental challenges such as population growth, energy demand, and water availability. Through such engagement, policy makers will come to appreciate the uncertainties we face in making predictions in an era of rapid environmental and social change.

[32] J. J. Thomas and K. A. Cook. 2005. National Visualization and Analytics Center. *Illuminating the Path: The Research and Development Agenda for Visual Analytics.*

JUPITER

PAIGE WARREN, UNIVERSITY OF MASSACHUSETTS-AMHERST

Environmental Decision-Making in a World of Uncertainty

Our increasing knowledge of the causes and consequences of environmental change and variability motivates a need to better understand how decision makers, from individuals to groups in both public and private roles, make choices among alternative courses of action. Integral to this process is interdisciplinary research to understand decision making under uncertainty and to develop tools to bridge the gap between scientists and decision makers.

The arid southwestern U.S. has seen an explosion of urbanization; the region is home to 8 of the 10 fastest-growing cities in the nation. Arizona's desert capital, Phoenix, is the largest city in the southwest with an urban population that has doubled twice in the past 35 years and is characterized by rapid expansion into former agricultural and pristine settings. The Phoenix metropolis faces much climatic uncertainty caused by inter-annual variation in precipitation endemic to desert climates, global climate change, and meso-scale anthropogenic forcing, such as the urban heat island effects and land use change-induced changes in water vapor, which individually and combined influence water availability.

Researchers at the Decision Center for a Desert City[33] (DCDC) at Arizona State University use Phoenix as a platform for studying adaptation strategies in the context of central Arizona's rapid population growth and urbanization, complex political and economic systems, variable desert climate, and the broader issue of global climate change. The DCDC project combines long-term environmental and demographic data with sophisticated simulation and modeling techniques to allow forecasting of various policy scenarios. Integrative outreach programs are used to engage policy makers and to foster collaboration between researchers and decision-makers in the region. Research products and decision-support tools, such as WaterSim—an interactive simulation of water supply and demand, can be adopted for desert regions worldwide.

Other projects focusing on environmental decision-making under uncertainty include: studying the limits in our understanding of climate change and its impacts;[34] integrating psychology and other social sciences into the design and testing of decision tools;[35] examining decision makers' expectations about what science can deliver and the effective communication and use of scientific data to and by policy makers;[36] and improving computer-based tools that enable decision-makers to make better choices when confronted with deep uncertainty about the future.[37]

[33] http://dcdc.asu.edu/

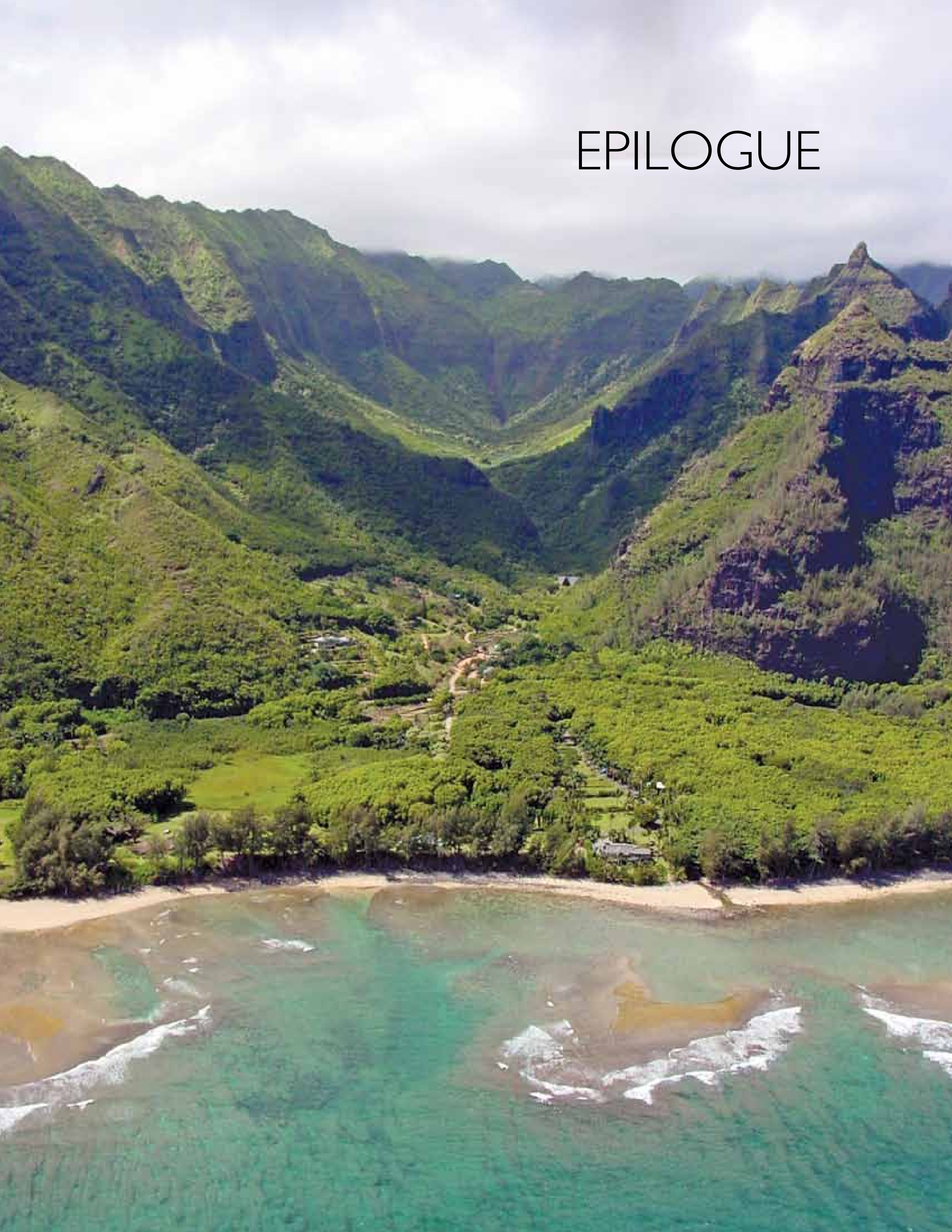
[34] Carnegie Mellon University's Climate Decision Making Center focuses on studying the limits in our understanding of climate change and its impacts. Researchers are developing and demonstrating methods to characterize irreducible uncertainties, focusing on climate and technologies for mitigation. They also develop and evaluate decision strategies and tools for policy makers that incorporate such uncertainties. http://cdmc.epp.cmu.edu/

[35] The Center for Research on Environmental Decisions (CRED) at Columbia University studies decision-making processes on multiple scales, focusing on integrating psychology and other social sciences into the design and testing of decision tools as well as institutional strategies and educational interventions that help people better understand the impacts of global climate change and their response options. http://www.cred.columbia.edu/

[36] The University of Colorado's Science Policy Assessment and Research on Climate (SPARC) team examines decision makers' expectations about what science can deliver, whether policy makers can use available information, and what future information might be useful to them. http://sciencepolicy.colorado.edu/sparc/

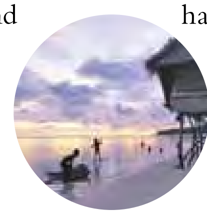
[37] Rand Corporation researchers are working on improving computer-based tools that enable decision makers to make better choices when confronted with deep uncertainty about the future, effective representation of uncertain scientific information for decision makers, and strengthening the scientific foundations of robust decision-making. http://www.rand.org/ise/projects/improvingdecisions/

EPILOGUE



IN A DISTANT REGION of the world a whole nation is making plans to avoid extinction. Kiribati, in the warm equatorial Pacific Ocean, is experiencing climate change as an obvious and inescapable threat. With only 811 square kilometers of land on thirty-three islands, mostly atolls, the majority of Kiribati's land is less than 2 meters above mean sea level. As the first nation to ring in the new millennium in 2000, it is likely that Kiribati won't survive the 21st century. With projected sea level rise of half a meter over the next century, not only will a substantial proportion of Kiribati's land be submerged but what is left will be degraded due to groundwater salinization, affecting freshwater availability and subsistence agriculture. Coral bleaching, higher tides, and a recent year-long drought also illustrate increased environmental challenges.

President Anote Tong has laid out a plan that would scatter his people to the winds, sending them throughout the nations of the world as rising sea level claims Kiribati's islands. Unable to find another sovereign home for all 100,000 of his people—the initial preferred option to preserve their culture and social ties—Tong has begun moving smaller groups of people abroad for job training and resettlement.



NATIONAL TROPICAL BOTANICAL GARDENS AND THE CENTER FOR CONSERVATION RESEARCH AND TRAINING, UNIVERSITY OF HAWAII

Despite their own fate, the people of Kiribati have taken action to preserve their coastal ecosystem: they have established the world's largest marine protected area. The Phoenix Islands Protected Area (PIPA) covers 255,000 square kilometers, a California-sized marine sanctuary that has set a new standard for conservation efforts around the globe. Soon the ocean PIPA protects will be all that's left of Kiribati.

As his nation disappears, Tong offers thoughts for consideration by the rest of the world: What do we do—wait for the water to come, then let them drown? To do nothing in the face of today's environmental challenges would be among humanity's most foolhardy choices.

From global climate change to alterations in land-use patterns driven by population growth and development, Earth is becoming a different planet—right before our eyes. The complicated and global scale of connectedness and rates of environmental change are beyond anything in recorded human history. Wherever we look, from Canada to Chile, from Kazakhstan to Kansas, we are witnessing a changing planet. What will it look like in the years, decades, and centuries to come?

NASA

RICHARD WILDER


KIRITOURS.COM

"If we want things to stay as they are," writes Thomas L. Friedman in his 2008 best-selling book *Hot, Flat, and Crowded,* "that is, if we want to maintain our technological, economic, and moral leadership and a habitable planet, rich with flora and fauna, leopards and lions, and human communities that can grow in a sustainable way—things will have to change around here, and fast."[38]

Our challenge is not simply that things are changing fast; there is large uncertainty as to how fast and to what consequences. Human impacts have created a situation without precedent on this planet. Neither current nor past rates of change are dependable guides to what might occur in the future. Feedbacks among environmental processes may accelerate rates of change. Of greater concern is that we may reach critical transition points—tipping points—beyond which abrupt, possibly irreversible changes will ensue.

The way forward requires an improved understanding of Earth's complex environmental systems; systems characterized by interactions within and among their natural and human components that link local to global and short-term to long-term phenomena, and individual behavior to collective action.

The president of Kiribati hopes to relocate his entire country. With sea level on the rise, the islands soon will be under water. But most countries cannot ride a wave of climate refugees enveloping the world. On this day, in this month, in this decade, we will make decisions affecting the future course of life on Earth.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[38] Page 7, Friedman, T.L., 2008. *Hot, Flat and Crowded: Why We Need a Green Revolution—and How It Can Renew America.* MacMillan; Farrar, Straus and Giroux Publisher, 448 pp.

Glossary

Anthropocene:
The most recent period of Earth's history, generally referring to the past two centuries, characterized by human activities having a substantial impact on global ecosystems and climate.

Anthroposhere:
A division of the Earth referring to that part of the environment made by or strongly shaped by human activities.

Complex System:
A set of multiple, diverse, and interacting components whose overall (system level) behavior is not predictable from measurement of the components alone. Complexity arises due to nonlinear responses and feedbacks among the system components. Complex systems are typically also complicated systems in that a large number of different components may be involved and operate over a range of different spatial, temporal, and organizational scales.

Complex Adaptive Systems:
Complex systems that include components having the capability to learn from experience, e.g., living organisms or human systems, and change in response to overall system level behavior.

Coupled Natural-Human Systems:
Complex Adaptive Systems characterized by geophysical and ecological components (natural systems) that are strongly linked to human and social system components.

Cyberinfrastructure:
The set of interoperable connections of electronic hardware and software that enables data acquisition, storage, management, mining, integration, and other data processing services and provides new tools for people to discover, learn, teach, collaborate, disseminate, access, and preserve these data and the knowledge derived thereof.

Ecosystem Services:
The resources and services provided to humans from natural ecosystems; these can be subdivided into provisioning (e.g., water, food), regulating (e.g., flood control), supporting (e.g. pollination), cultural (e.g., recreation), and preserving (e.g., resiliency to disruption) services.

Interdisciplinary Research:
The integration of approaches, concepts, and data from multiple science and engineering disciplines to advance understanding and address problems in a fashion that is more comprehensive and synthetic than is possible using only the perspective of a single discipline.

Resiliency:
The ability to recover from disruption, or the rate of its return, to some prior state following a perturbation.

Sustainability:
The ability to continue or persist into the long-term while maintaining a particular set of characteristics or functionalities. Sustainability may involve components or mechanisms that promote resiliency but is a broader concept than just recovery from perturbation.

Tipping Point:
The point at which a system undergoes a drastic change from one state to a very different one. Complex systems involving positive feedback among components with non-linear rates of change are susceptible to tipping point phenomena. The term was made popular by Malcolm Gladwell in his 2000 book "The Tipping Point: How Little Things Can Make a Big Difference", which discusses the concept with respect to change in human behavior and social systems.

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