XE: Extreme Events
Developing A Research Agenda For The 21st Century
Workshop Report:

Integrated Summary

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A Framework for Organizing, Integrating
and Ensuring the Public Value of Research

Background and Executive Summary

Extreme events are an emerging and unifying theme in scientific research. Investigations into complex systems yield increasing evidence that system evolution is strongly controlled by extreme events, and increasing insight into how extreme events come about. At the same time, natural and technological disasters, complex civil emergencies, and infectious disease epidemics are all on the upswing. Scientific and societal interest in extreme events are converging, and the time is ripe for focused action.

More than thirty scientists and practitioners spent three days discussing the issue of extreme events, as a first step toward developing a research program. The goal of the workshop was to view extreme events through as many disciplinary and societal lenses as possible, and to use these diverse perspectives to build a comprehensive framework that could guide scientifically exciting and societally relevant research. Participants were drawn from:

- computer science,
- ecology,
- political science,
- mechanical engineering,
- seismology,
- volcanology,
- philosophy,
- psychology,
- economics,
- anthropology,
- meteorology,
- sociology,
- epidemiology,
- paleoclimatology,
- atmospheric science,
- physics,
- geography,
- remote sensing,
- computer system management,
- emergency management,
- and international aid.

While this group may not have represented every possible perspective on extreme events, it did bring an extraordinarily rich menu of interests, experiences, and expertise.

From this diversity came the recognition that extreme events are not isolable phenomena, but in fact must be understood and addressed in terms of interactions among different types of systems. While many specific research problems were suggested at various times during the workshop, the group invariably treated these problems as part of this larger context of complex interactions. A key implication of this insight is that an effective framework for extreme events research must create interdependence among scientific investigation, information integration, knowledge transmission, and decision-making. The organizing principle that can unify these often-distinct activities is vulnerability; that is, a system's susceptibility to change under the impetus of an extreme event. Within such a framework, science can flourish, and society can benefit.

Introduction: Extreme Events as a Research Focus

This report presents a framework for thinking about why and how to organize a research agenda on extreme events. It is a guide for research planning, not a prescription for particular research projects (although many ideas for specific projects are implied by the discussion). The goal of the report is to articulate a convincing intellectual and organizational structure for an extreme events research program in the context of societal needs.

Extreme events are critical determinants of the evolution and character of many-perhaps most-natural and human-influenced systems. Conversely, it is no overstatement to suggest that humanity's future will be shaped by its capacity to anticipate, prepare for, respond to, and, when possible, even prevent extreme events. From such a perspective, extreme events emerge as a powerful focus for organizing research activities that can advance scientific knowledge and directly benefit society.

Sixty-five million years ago, a huge asteroid collided with the earth and radically transformed the path of biological evolution. One result of this ecological cataclysm was the extinction of dinosaurs and the rise of mammals, culminating eventually in the emergence of *Homo sapiens* as the dominant life form on the planet. Humanity thus owes its existence to an extreme event in geologic history.

Science seeks to make natural and human-influenced systems comprehensible and manageable. Yet, as the asteroid story vividly illustrates, the character of such systems may be determined by infrequent, high magnitude occurrences whose causes and effects may not be easily inferred from the "normal" behavior of the system itself. "Extreme events," that is, can introduce both profound change and enormous contingency into the evolution of any system.

Because extreme events can strongly determine the character of both natural and human-influenced systems, and because the effects and attributes of such events cannot necessarily be inferred from the "normal" behavior of the system, research focused on a system's "normal" behavior will not characterize the full range of possible system dynamics. For example, patterns of biological evolution cannot be understood without also understanding the role of asteroid impacts. (More prosaically, understanding the erosion of beaches depends on understanding the impacts of large coastal storms, and understanding the history of human populations depends on understanding pandemics and wars).

Yet an extreme event is not simply "something big and rare and different." "Eventness" demands some type of temporal and spatial boundaries, while "extremeness" reflects an event's potential to cause change. Both "extremeness" and "eventness" derive from the human perception of consequences, which in turn reflects the character of the affected system. An asteroid moving through space is neither extreme nor an event. An asteroid striking Earth and altering the course of evolution is both. Similarly, while a powerful hurricane is undoubtedly a "normal" occurrence on Earth, only when this hurricane strikes a populous city do its "extremeness" and "eventness" command broad attention and demand both comprehension and action. Yet it is precisely the magnitude and infrequency of such storms, as measured on human space and time scales-or of cataclysmic asteroid impacts, measured on geological time scales-that makes it difficult to acquire comprehensive understanding.

Extreme events are inherently contextual and relational. Studying an extreme event independent of its context provides at best incomplete knowledge, because the character and significance of any such event is determined by its relation to the system it is affecting. In many cases, indeed, the extreme event does not exist independent of its context. For example, as a consequence of European exploration and colonization of other lands, infectious diseases that were held in check in European populations by acquired immunity or heritable patterns of resistance were disastrously transmitted to nonresistant populations elsewhere. In Europe, such diseases may have been chronic problems, but in the Americas they became extreme events. Extreme events reflect not just actions, but interactions, and the emergent properties of those interactions. Such complexity adds an even greater challenge to the scientific understanding of extreme events and their consequences.

The capacity of society to understand and manage its affairs depends in no small part on its ability to understand, anticipate, prepare for, and respond to extreme events. Regional armed conflicts, infectious disease epidemics, high-impact weather and geologic events, technological disasters, computer network failures, and the collapse of local and regional ecosystems are examples of extreme events whose significance for humanity are likely to increase in coming decades. Moreover, increasing cultural, economic, and technological interconnectedness may create more possibilities for cascades of extreme events, such as the El Niño-related drought in Indonesia in 1998, which contributed directly and indirectly to fire, food shortages, economic downturn, civil unrest, and political upheaval. The threat of the Y2K bug-and the massive societal response aimed at mitigating that threat-illustrated the comprehensive vulnerability to cascading technological extreme events created by society's growing dependence on complex information networks for managing its daily affairs.

Finally, because underrepresented and disenfranchised groups tend to be disproportionately vulnerable to the impacts of extreme events, a successful program of research and application aimed at reducing vulnerability can, if properly carried out, contribute over the long term to the reduction of inequity in society. Given that technological advance has arguably played a role in the increasing polarization of wealth, health, and environmental quality in the U.S. and throughout the world, extreme events present a countervailing opportunity to demonstrate the value of science to *all* sectors of society.

Extreme Events as an Integrating Research Theme

Many fields of inquiry and practice have contributed to scientific understanding and societal response to extreme events. Individual science and engineering disciplines, as well as multidisciplinary approaches emerging from such fields as natural hazards and complexity, are now at the point where major advances in the integration and application of knowledge of extreme events is both desirable and possible. Traditionally independent lines of research and practice are converging on common themes, insights, and methods in their efforts to understand extreme events. This emerging, transdisciplinary coherence derives from the following characteristics:

1. Extreme events are often distinct from the "normal" or "usual" behavior of complex systems, yet they may have a formative influence on system evolution and character.
2. Extreme events often reflect interactions between different types of systems. Understanding extreme events is thus an intrinsically interdisciplinary goal. For example, research on algal blooms may require not simply knowledge of the local ecology of the algae, but also of the biogeochemical cycles that control nutrient production, the hydrological character of the aqueous system, and the local and regional climate conditions.
3. Researchers in diverse fields are applying similar tools (e.g., statistics, mathematical models, complexity theory) to the investigation of a great variety extreme events. These various tools share a need for similar technologies and techniques (e.g., observations, data assimilation, supercomputing, visualization).
4. Researchers in diverse fields are seeking to distinguish extreme events that are potentially predictable from those that are understandable but not predictable, as part of a broader effort to enhance the forward-looking capability of human decision-making.
5. Researchers in diverse fields are examining how decision-making processes, and the institutions in which such processes occur, strive to meet the challenge of preparing for extreme events under conditions of uncertainty.
6. Very different types of extreme events have very similar immediate consequences for decision makers, be they emergency managers, military officers, or computer network operators. For example, response capabilities during extreme events are often overwhelmed and resources are inadequate; new and unfamiliar problems emerge; reliable information is difficult to acquire; and a coherent view of the situation is impossible to construct.
7. Very different types of extreme events have very similar longer-term consequences for society. A computer virus and a flood may have nothing in common in terms of causes, but both might, for example, lead to the shutdown of a community's water treatment plant, with identical societal consequences and demands for response.
8. The growth of societal networks of every kind (information, communication, transportation, etc.), the progressive interpenetration of natural and artificial systems, and the continually increasing complexity of human organizations and institutions promises to magnify the impacts-and generate new types and combinations-of extreme events.

These characteristics demonstrate that extreme events are a powerful theme for integration and application of research across all the National Science Foundation research directorates, connecting such disparate fields as anthropology, cognitive science, complexity science, computer science, ecology, economics, civil and mechanical engineering, epidemiology, geosciences, political and policy science, probability and statistics, psychology, and sociology.

Extreme events also offer a context for advancing and integrating recent technological advances in computer modeling, remote sensing, visualization, early warning systems, and decision support systems. Given their obvious public appeal (hurricanes, asteroid impacts, nuclear disasters, computer crashes, and volcanoes have played leading roles in recent movies), extreme events should be promoted as an intrinsically integrative focus for K-12, undergraduate, and graduate education, one that is well-suited for advancing general understanding of science and technology and enhancing critical thinking skills. As a whole, a well-structured extreme events program has the potential to leverage societal benefit from an integration of knowledge, theory, and practice that could not be achieved through more traditional, balkanized disciplinary approaches.

Organizing Integrated Research on Extreme Events

I. Vulnerability: An Organizing Principle

An extreme event presupposes its impact on a natural or human-influenced system. This impact reflects-exists because of-*vulnerability* to the event (recall the susceptibility of dinosaurs to meteors; or of indigenous Americans to European pathogens). In this context, vulnerability refers to a system's susceptibility to change as a consequence of an extreme event. The *state* of vulnerability therefore lies at the core of any integrated approach to generating knowledge and stimulating action on extreme events.

Vulnerabilities often mark the interface between different systems or system elements: a town (cultural), a beach (geological), and a hurricane (meteorological); an information network (technological), an industry (economic), and a computer failure (technological). Strong El Niño-La Niña cycles (climate systems) can have a devastating impact on reefs and fisheries (ecosystems). Wetlands, beaches, estuaries, mangrove swamps, and other transitional environments can be profoundly transformed by extreme weather events, and by technological disasters such as oil or other toxic spills. *Understanding* vulnerability thus requires knowledge of the behavior and interactions of all systems involved in an extreme event; vulnerability is an organizing principle for extreme events science.

When extreme events are considered in terms of their impact on society, then *reduction* of vulnerability can act as a principle for unifying science and societal action. Reduced vulnerability can be achieved through many avenues, including evolutionary processes (e.g., increased resistance to disease); preventing the extreme event (or modifying it to make it less extreme); reducing vulnerability before the event occurs (e.g., engineering structures to resist wind and ground-shaking); responding effectively to the extreme event after it occurs (and thus reducing the duration that the affected systems are disrupted); and avoiding the extreme event (e.g., through evacuation).

Opportunities to reduce vulnerabilities are often created by extreme events. The 1970s oil crises were extreme events made possible by U.S. dependence on foreign oil (vulnerability), but they created new and unexpected opportunities to boost energy efficiency and encourage development of new technologies. Technological disasters such as oil spills have prompted better safety regulations; earthquakes have led to stronger building codes.

Integrated scientific understanding of extreme events can help both to characterize and monitor vulnerability and determine alternative strategies for reducing it. To reach this potential, any integrated research focus on extreme events will require partnerships among diverse sectors of society including research institutions; local, regional, and national public-sector decision-making bodies; and public- and private-sector organizations that help protect against and respond to extreme events.

Consider, for example, the types of knowledge and practice necessary to reduce vulnerability to earthquakes. Such an effort requires some knowledge of spatial distribution of seismic events, as well as frequency and magnitude probabilities (seismology); knowledge of the behavior of soils and rocks during shaking, and distribution of soils and rocks (geology, soil science, geotechnical engineering); characterization of building stock and behavior during shaking (seismic engineering); development of standards for engineering structures (engineering, statistics); development and enforcement of building codes (engineering; public policy); communication of risks and response strategies to the public (communications; media); management of risk through mechanisms like insurance (economics, decision theory, public policy); and so on.

Yet such directly related knowledge is not enough. Continued progress in reducing vulnerability-and the successful application of disciplinary and multidisciplinary knowledge to this goal-also demands an understanding of social systems, group behavior, and politics. Why, for example, does society preferentially reduce the vulnerability of some socioeconomic or cultural groups, while neglecting others? Why do people preferentially migrate to coastal areas? Why don't people take cost-effective measures that can reduce their vulnerability? In summary, the concept of vulnerability, and the goal of reducing it, can exert a centripetal organizational force leading to a comprehensive, integrated, multisectoral approach to extreme events.

II. Decision Processes: A Fundamental Unit of Analysis

Reduction of vulnerability occurs through decision-making processes that include appropriate application of available knowledge before, during, and after events. Therefore, a research focus on extreme events will recognize that decision processes are the fundamental unit of analysis in the quest to generate, integrate and apply knowledge.

For example, consider the pre-event decision of whether or not to issue a hurricane evacuation warning. This decision process is informed by many types of knowledge, for example: likely future track and intensity of the storm (meteorology); vulnerability assessment of the potentially affected communities (engineering, hydrology, etc); the specific message and media to be used for passing information from one party to another (communication, information technology); mechanics of evacuation (transportation, engineering, etc.); expectations about the public response to evacuation orders (sociology), and sensitivity to political constraints and power structure (political science). The decision process is also shaped by general knowledge independent of any particular storm, such as climatology, risk assessment, economics, and science policy priorities.

Or consider challenges facing emergency managers during complex civil disturbances or other disasters. They must decide how to allocate resources in order to minimize injuries, damage, recovery time, and recovery costs. Experienced managers can call upon decision heuristics and professional intuition as a guide, but they can also benefit from knowledge about the immediate and evolving effects of the extreme event, which in turn requires real-time information about the event itself (magnitude, distribution, duration), the distribution of vulnerability, and the availability of resources. Less obviously but just as importantly, the successful application of such real-time information also depends on knowledge about development and application of ethical and professional standards, distribution and use of knowledge by complex organizations (including political institutions), management of complex, evolving systems, etc.

Decisions may also increase vulnerability. People often make choices that neglect to account for extreme events, such as building houses in a flood plain, a beach, or a fire-prone forest. Politicians, land managers, and other decision makers may get more credit for responding to disasters than preventing them. Companies make decisions that favor short-term profitability over long term safety. Such decisions may be overt or unconscious. Computer networks are permeable to viruses and prone to failure because no one anticipated the kind and scale of use they now support.

In the real world, extreme events pose complex, ill-structured problems for individuals and organizations whose capacity to act reflects not only what is known or not known, but also external constraints that have little to do with the extreme events themselves. Under the pressure of an extreme event, decisions will be influenced by social, professional, socioeconomic and political relations, organizational structures, and prior experiences. In other words, decisions are highly contextual, and understanding context will be central to understanding decisions. For example, the willingness of decision makers to act on new information may strongly depend on the level of trust they have for those who deliver the information, which may in turn reflect a history of prior interaction. And even the concept of a "decision maker" is inherently complex and nuanced. In any organizational context, decisions are usually "made" through complex interactions among a variety of participants, few or none of whom will have a comprehensive view of the entire situation and many of whom operate under significant constraints.

In other words, decision processes are naturally and necessarily integrative; they are an interface between information, action, and societal impact-between knowledge and the reduction of vulnerability. Moreover, decisions are made in a great variety of nested contexts, from individual to group to organizational to broader sectors of society. By asking basic questions focused on decisions in the context of extreme events (e.g., who is participating in the decision process? What would be a good decision? What knowledge would be needed to improve it? What are the alternatives? What conditions foster the best decisions?), a comprehensive research agenda can emerge. Such an agenda is not an alternative to disciplinary research, but a complement: a framework for problem choice, integration and application.

III. Knowledge Integration Tools, Techniques, and Processes

What allows scientific research to discover facts about extreme events? What translates those facts into knowledge that is useable by other scientists and by decision makers? The characteristics of "extremeness" and "eventness" throw several challenges in the path of efforts to acquire understanding. Extremeness implies greater than "normal" magnitude; eventness implies rarer than "normal" frequency. Direct observation and experience is thus impeded. Furthermore, because extreme events often reflect the interaction of complex systems, standard disciplinary, reductionist and experimental approaches to knowledge acquisition may have limited utility.

How are these challenges overcome? For extreme events, four integrating mechanisms seem particularly important: modeling, predictions, integrative observation, and acquired (experiential) knowledge. Figure 1 shows one way to think about the integrating role of these mechanisms. They permit disparate scientific disciplines to work together; of equal importance, they are the heart of a continual feedback process than can link science to decision making, given the appropriate institutional structures (see IV, below).

A. Modeling: One salient feature of extreme events is relative infrequency of occurrence. As a result, scientists and decisions makers often have limited observations, data, and experience. Computer models are one approach to overcoming this limitation.

There are two types of models, consolidative and exploratory. A consolidative model seeks to include all relevant facts into a single package and use the resulting system as a surrogate for the actual system. The canonical example is the controlled laboratory experiment. Other examples include weather forecast and engineering design models. Such models are particularly relevant to decision making because the system being modeled can be treated as being fully characterized, or closed. Such models can be used to investigate diagnostics (i.e., "what happened?"), process ("why did it happen?"), or prediction ("what will happen?").

An exploratory model is one in which all components of the system being studied are not established independently or are not known to be correct-as is most often the case for extreme events, and for complex systems in general. Exploratory models allow for computational experiments that investigate the consequences of various assumptions, hypotheses, and uncertainties associated with the creation of and inputs to the model. These experiments can shed light on the existence of unexpected properties associated with the interaction of basic assumptions and processes (e.g., complexity or surprises); they can facilitate hypothesis generation; they can help characterize limiting, worst-case, or special scenarios under various conditions; and they can identify potential precursors to extreme events (e.g., behavior of markets prior to disruptive sell-offs; social, political, and environmental conditions leading up to civil wars).

If models are to be valuable inputs for decisions, then modelers must understand both the limits of their own models, and the information needs of decision makers. Consider FEMA's HAZUS model, which assesses the distribution of impacts from natural disasters, and can be used as a decision support tool for emergency managers. The model was developed through collaboration between engineers, political scientists, economists, emergency managers, and modelers. Although HAZUS is far from perfect (it is not consolidative), it can augment the heuristics and professional intuition of decision makers during the early stages of a disaster, when reliable, on-the-ground information is typically missing.

B. Predictions: Because decision-making is inherently forward-looking, scientific predictions (often generated by consolidative or exploratory models) have the potential to benefit the decision process. This potential is especially appealing in the case of extreme events, because of their rarity and the potential severity of their impacts.

Characterizing the predictability of an extreme event can help determine productive avenues for both additional research and reduction of vulnerability. Characterizing predictability in relation to "understandability" yields an even greater level of insight for further action. For example, earthquakes are reasonably well understood in terms of mechanism and distribution, but they are thus far unpredictable. Reduction of vulnerability thus appropriately focuses on application of probabilistic models for structural design, vulnerability assessment, and post-disaster recovery rather than on evacuation plans or highly site-specific hazard mitigation. Similar approaches could be applied to a broad range of extreme events.

The four permutations of predictability and understandability are in reality more of a continuum than a set of mutually exclusive conditions:

1. Predictable and understandable. Observations and consolidative models render some phenomena (e.g., floods; Y2K; hurricane landfalls) reasonably predictable.
2. Predictable and not understandable. Time sequence data and other empirical data may render some extreme events generally predictable even if they are not understood. For example, the course of AIDS in Africa was predicted a decade in advance, even though

the mechanisms of disease transmission were not well elaborated.

3. Understandable and not predictable. Extreme events may be recognizable as emergent properties of complex systems, and describable in terms of simple magnitude-frequency curves and power laws, yet still defy prediction (e.g., earthquakes; technological disasters). Such phenomena may yield to probabilistic approaches, such as engineering and actuarial techniques for dealing with uncertainty.
4. Not understandable and not predictable. Some systems are simply too complex to allow even the development of convincing probabilistic approaches to extreme events, for example the long term behavior of ecosystems, nuclear waste repositories, or large organizations. In these situations, decisions may have to depend on trial-and-error, adaptive management, and other evolutionary or redundancy-based strategies.

If predictions are to play a role in decision making, they cannot be viewed simply as numbers with attached uncertainties. Rather, predictions must be recognized as part of a decision process. In northeastern Brazil, for example, droughts are historically common and local farmers have developed ways to cope with them as they occur. The introduction of seasonal drought forecasts was meant to help farmers plan their plantings more successfully, but in fact the farmers lacked technology and economic flexibility necessary to benefit from the forecasts. In the end, the timing, uncertainties, and utility of the forecasts were all incompatible with the needs of the farmers, who in turn lost confidence in the meteorological agency distributing the forecasts, and in the forecasts themselves. The problem was that the science was aimed at *good forecasts*, rather than *good decisions*.

Predictions can act as an integrative mechanism for linking science to decision making if predictive science is carried out in light of the following:

1. Predictions must be generated primarily with the needs of the user in mind. Stakeholders and scientists work together closely and persistently to communicate capabilities, needs and problems.
2. Uncertainties must be clearly articulated (and understood) by the scientists, so that users understand their implications. Failure to understand uncertainties can contribute to poor decisions and undermine relations among scientists and decision makers. But merely understanding the uncertainties does not automatically mean that the predictions will be useful (e.g., if uncertainties are very high, or if the prediction does not address decision maker needs).
3. Experience is an important factor in how decision makers understand and use predictions. For extreme events that occur relatively frequently (e.g., hurricanes), decision makers can accumulate experience that allows them to evaluate and appropriately make use of the prediction, and respond more effectively after the event takes place. In other situations (e.g., asteroid impacts; nuclear disasters), personal experience may not exist, and decision rules will not be available.
4. Predictions themselves are events that cause impacts on society and stimulate decision making. Incorrect predictions may create considerable costs (e.g., an unnecessary evacuation) and may also affect the subsequent behavior of individuals and institutions (e.g., resistance to future evacuations).

C. Observations-Acquisition and integration of data: Technological advance permits the acquisition of increasingly comprehensive suites of observations before, during, and after extreme events. From high resolution satellite data that can track the course of hurricanes, fires, droughts, oil spills, volcanic ash plumes, or refugee populations, to worldwide seismometer arrays and nationwide stream gage networks, huge amounts of multidisciplinary observational data can now be fed into computer models and prediction algorithms, or directly into decision processes. Visualization and decision support technologies can integrate data from different sources to give synoptic views of evolving conditions prior to, during, and after an extreme event. Early warnings of famine, civil disturbance, epidemics, and other extreme events are now being realized by combining information from advanced observational technologies with empirically derived criteria for recognizing event precursors.

The key issue is how to develop, integrate and present information in ways that are useful to decision makers. Observational technologies are tools that can contribute to this process, but the information they generate must match the needs and capabilities of information users. New technologies increase the volume and diversity of observational data, but application depends on effective communication between providers and users to determine a) What types of data are most needed, and when?; and b) How should this data be presented to be most useful? Different decision makers operate under different sets of rules and capabilities. Following recent catastrophic flooding in Mozambique, efforts to transmit digital satellite data to emergency planners paralyzed the nation's computer networks, creating a second (albeit minor) extreme event. During the 1997 Red River Flood in North Dakota, copious observational data about river conditions were available, but weather forecasters and local decision makers communicated poorly, thereby magnifying the scale of the disaster.

A related issue is that the types of data that can be acquired can influence the priorities of the decision process. For example, "high-end" vulnerability and damage (e.g., large buildings, bridges, dams, computer networks, power grids) are often easier to assess than "low-end," (e.g., individual homes, small roads, water wells). This can mean that, while underrepresented and disenfranchised populations suffer disproportionately from extreme events in any case, the low visibility of the infrastructure and networks upon which such populations depend can further exacerbate such inequities. Understanding levels and distribution of vulnerability in a community may require intimate knowledge of the social structure of that community that can only be acquired through direct experience, dialogue with local decision makers, and field observation. Such knowledge may in turn be necessary to help determine the types of observational information that can reduce vulnerability, and the manner in which such information is best communicated.

D. Acquired Knowledge, Decision Heuristics, and Intuition: Individual and group knowledge is a critically important element of understanding, preparing for and responding to extreme events. Such knowledge is acquired by experience and reflects the unique integrative capabilities of the human mind. For example, emergency aid organizers may recognize a predictable suite of diseases and atrocities that accompany complex civil emergencies. This "professional" knowledge may be sufficient basis for taking immediate action to reduce vulnerabilities and impacts, even if formal decision protocols demand a more empirically rigorous assessment.

On the other hand, important aspects of many extreme events may be unique-indeed, it is that very uniqueness that makes them extreme. For example, the Oakland Hills fire of 1991 quickly achieved a scale unprecedented in the experience of regional firefighters. During such events, decision heuristics and intuition may be insufficient, or even counterproductive, guides to action.

Decision heuristics and scientific knowledge may or may not be compatible. Local communities may possess knowledge and decision processes for dealing with extreme events that are destabilized, rather than supported, by the introduction of new types of information.

Citizens may resist evacuation orders in accordance with values, priorities, and experiences that are not incorporated in disaster planning models. Farmers may have mechanisms for coping with drought that are actually disrupted by external aid programs.

In summary, modeling, predictions, integrative observation, and acquired knowledge are each potentially important components in the complex process of developing and using knowledge about extreme events. However, the appropriate design, role, and application of these integrating mechanisms-including their relations to each other-is far from well understood.

IV. Creating Useable Knowledge

> *"If you know the answer, how come I don't?"*
> —emergency manager of a large, extreme-events-prone U.S. city.

If decision processes are the fundamental unit of analysis for an integrated extreme events research program, then the central challenge of such a program is to generate knowledge that contributes to better decisions. Doing so requires organizational and institutional arrangements that bring investigators and decision makers together, so that each can understand the needs and capabilities of the other. Such arrangements call for innovative changes in the structure of standard research programs, such that "living with users" becomes an integral part of the research process. The previous discussions identify numerous places within an integrated extreme events research program where such cohabitation could productively take place.

More fundamentally, the relation between "more information" and "better decisions" relevant to extreme events is insufficiently understood. We need to know more about how and when providing information actually improves decisions, and about the types of information (and modes of presentation) that are most efficacious. Such understanding in turn requires a better understanding of the behavior and interactions of relevant individuals, organizations, and sectors. For example, the media often plays a formative role in both bringing public attention to, and influencing the evolution of, extreme events. In an open society, the relation between researchers who supply information and decision makers who consume it can be made enormously more complex by media coverage of, say, a predicted extreme event (e.g., Y2K). U.S. intervention in Kosovo (and the subsequent Serbian expulsion of the Kosovars) was arguably precipitated by media coverage. Understanding such complexities is an essential component in the broader process of creating useable knowledge.

The quest for useable knowledge presents a significant challenge for research planning and conduct. This report suggests that any reasonably comprehensive approach to understanding and responding to extreme events will have to develop innovative institutional mechanisms and cultural incentives for integrating knowledge creation and knowledge application. Such approaches can lead to great advances for science and society.

This report is based on a workshop held in Boulder, Colorado, on June 7-9, 2000. The report was prepared by Daniel Sarewitz (Center for Science, Policy, and Options, Columbia University) and Roger Pielke, Jr. (Environmental and Societal Impacts Group, National Center for Atmospheric Research). This version of the report reflects comments received from 20 workshop attendees.

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