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Extreme Events: A Research and Policy Framework for Disasters in Context

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Abstract

Extreme events are significant determinants of the character and evolution of many natural and human systems. When extreme events occur at the interface between natural and human systems, they are often called "disasters." Here, we use a systemic, contextual view of disasters to construct a framework for organizing research and policy. Within this framework, reduction of vulnerability is the organizing principle, and decision processes (which lead to reduced vulnerability) are the fundamental unit of analysis and action. Scientific research is connected to decision processes through knowledge-integrating activities such as prediction, observation, and heuristics. But the value of research depends on its capacity to enhance decision-making capabilities. Our goal is to define an approach by which policy-relevant research questions can be more readily recognized, and societally valuable (i.e., vulnerability-reducing) knowledge can be more effectively created and used.

Introduction

THE GROWING TOLL of disasters around the world presents a challenge for public policy, scientific research, and their interconnections. Policy seeks to reduce the human and economic effects of disasters; research seeks to provide knowledge and tools that can contribute to the effectiveness of policy. These challenges emerge in the face of societal trends that are converging to increase the likelihood, magnitude, and diversity of disasters. Growing population, migration of population to coasts and to cities, increased economic and technological interdependence, and increased environmental degradation are just a few of the interacting factors that underlie the mounting threat of disasters (Red Cross, 1999; Center for Research on the Epidemiology of Disasters, 2001).

Rising societal exposure to disasters commands greater attention to their causes and to their mitigation. Yet there is something not quite right about this traditional formulation of the problem, which posits disasters as discrete phenomena that are external to the social or environmental systems upon which they impinge. According to this approach, disasters and society are related to one another in a linear, cause-and-effect manner. Disasters can therefore best be studied through disciplinary investigation based on physical attributes inherent in the relevant phenomena: seismologists study earthquakes; meteorologists study storms; hydrologists study floods; nuclear engineers study meltdowns; etc. Hazards are reduced by application of such research to mitigation programs and other policy approaches.

The reality of rising disaster impacts points to a different way to view disasters: not as individual isolatable phenomena, but as emergent properties of interactions within or between complex, dynamic systems. Consider the following three ingredients: a mega-city in a poor, Pacific rim nation; seasonal monsoon rains; a huge garbage dump. Mix these ingredients in the following way: move impoverished people to the dump, where they build shanty towns and scavenge for a living in the mountain of garbage; saturate the dump with monsoon rains; collapse the weakened slopes of garbage and send debris flows to inundate the shanty towns.

That particular disaster, which took place outside of Manila in July 2000, and in which over 200 people died (CNN.com, 2000), starkly illustrates our central point: disasters are characterized and created by context. Disaster was not inherent in any of the three ingredients of that tragedy; it emerged from their interaction. In a more general way, the changing demographic, economic, and environmen-

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tal conditions around the Pacific Rim, and indeed throughout most of the world, are the dynamic context within which disasters are created and experienced. From this perspective, every disaster is in some way *sui generis*, which suggests that research strategies organized around particular types of disasters might productively be reconceptualized in terms of a higher-level organizing principle.

Here, we present a framework for organizing research and policy related to disasters in a broader context—as extreme events linked to societal vulnerability via human decision-making processes. Our goal is to take advantage of emerging ideas from numerous disciplines in order to think about the linkages between scientific research and policy making relevant to hazard reduction. In particular, we hope to define a perspective from which policy-relevant research questions can be more readily recognized, and societally valuable knowledge can be more effectively created and used. Such a framework, consistent with the work of some of the leading voices in the diverse community of natural hazards scholars,[2] is timely not only because of the rising vulnerability to and consequences of disasters, but also because of an emerging commitment to societally relevant, problem-focused, interdisciplinary research in the scientific enterprise as a whole (e.g., Committee on Science, Space, and Technology, 1992; Pielke and Byerly, 1998; Branscomb, 1999; Gibbons, 1999; Frodeman and Mitcham, 2000). This commitment demands new ways of thinking about the organization of scientific inquiry.

An Integrated Framework for Research and Policy for Extreme Events

We define extreme events as occurrences that, relative to some class of related occurrences, are either notable, rare, unique, profound, or otherwise significant in terms of their impacts, effects, or outcomes. This somewhat tortured definition reflects the fact that extreme events are inherently contextual. That is, the character of an extreme event is determined not simply by some set of innate attributes, but by the interaction of those attributes with the system that it is affecting. For example, while the collision of an asteroid with the Earth 65 million years ago wiped out the dinosaurs and facilitated the rise of mammals, a kinetically similar collision between an asteroid and Jupiter would have had very different consequences.

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 typhoon is undoubtedly a "normal" occurrence on Earth, only when this typhoon strikes a populous coastal zone do its "extremeness" and "eventness" command broad attention and demand both comprehension and action.

Studying an extreme event independent of its context provides at best incomplete knowledge. 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 (McNeill, 1977). 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 and anticipation 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 is likely to increase in coming decades. Moreover, increasing cultural,

[2]The long history of distinguished research on natural hazards was reviewed by Mileti (1999). As well, within most academic disciplines there are scholars who focus on extreme events of one sort or another (Sarewitz and Pielke, 2000). Recognizing the depth and breadth of this scholarship, our purpose here is to build upon previous work to present a framework that allows for greater integration of knowledge across disciplines (e.g., physical, life, and social sciences, and engineering) for the explicit purpose of providing useful information to decision makers.

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 (Red Cross, 1999). 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. Yet the Y2K problem was of a rare variety in that its cause and solution were rooted in a single factor—the algorithm for embedding calendars into software—that was both recognized and correctable in advance.

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 the way that it deals with extreme events. 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. Given these observations, extreme events emerge as a powerful focus for organizing research activities that can advance scientific knowledge and benefit society.

From a scientific standpoint, extreme events are a potent organizing framework. Researchers in diverse fields are applying similar tools (e.g., statistics, mathematical models, complexity theory) to the investigation of a great variety of extreme events. These various tools share a need for similar technologies and techniques (e.g., observations, data assimilation, supercomputing, visualization). Conversely, and more challengingly, because extreme events reflect interactions between different types of systems, understanding them is 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, upstream irrigation, fertilization and farm policies, and the local and regional climate conditions.

Extreme events are also a potentially powerful framework for public policy. Very different types of extreme events have very similar immediate consequences for decision makers, be they emergency managers, military officers, factory managers, 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. Diverse extreme events may have similar longer-term consequences, as well. 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.

Overall, extreme events both demand and permit a unified framework for generating knowledge for the benefit of society. In the next three sections, we discuss the major components of such a framework.

Vulnerability: The Organizing Principle

The idea of 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). El Niño–La Niña (climate systems) can have a devastating impact on reefs and fisheries (ecosystems) (e.g., Normile, 2000). 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 systems involved in an extreme event; vulnerability is thus 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, e.g., Y2K reprogramming); reducing vulnerability before the event occurs (e.g., engineering structures to resist wind and groundshaking); responding effectively to the extreme event after it occurs (and thus reducing the duration and magnitude of disruptions); 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. Moreover, vulnerability may be accompanied by benefits: while floods may cause great damage to development along floodplains, they also restore and replenish soil and promote ecosystem health, and in this way are beneficial to humans (Haeuber and Michener, 1998). From yet another perspective, the vulnerabilities that we may seek to reduce to create benefit for some can also become opportunities for gain for others, as in the common situation when a disaster leads to subsequent infusion of economic development activity. So vulnerability itself should be understood as a contextual concept.

Integrated scientific understanding of extreme events can help both to characterize 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 such as insurance (economics, decision theory, public policy); and so on.

Yet such directly relevant 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.

Decision Processes: The Fundamental Unit of Analysis and Action

Reduction of vulnerability occurs through decision-making processes that translate knowledge into action before, during, and after events. Figure 1 is a schematic representation of one way to visualize the relations between knowledge integration, decision processes, and vulnerability reduction. In essence, effective decision processes are what permit connections between the generation, integration, and application of knowledge. For example, consider the emergency manager's pre-event decision whether or not to require a hurricane evacuation. This decision process is informed by many types of knowledge, including: 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 (including the emergency manager's experience), econom-

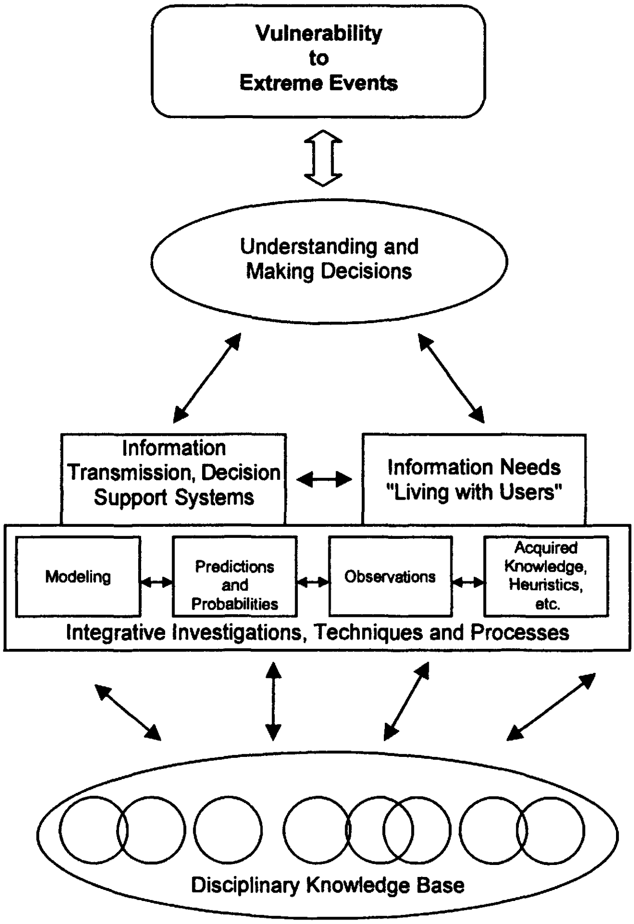

FIG. 1. Schematic research and policy framework for extreme events.

ics, and science policy priorities. All of these sources of information may have an influence on the evacuation decision.

Or consider challenges facing emergency managers during complex civil disturbances or other disasters. They must decide how to allocate finite resources to limit 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), and management of complex, evolving systems.

Decisions may of course increase vulnerability. People often make choices that neglect to account for extreme events, such as building houses on a floodplain, a beach, or in a fire-prone forest. Or people may lack the opportunity to make choices, or they may choose not to make choices. Poor policies and incomplete knowledge may exacerbate such problems. 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. Decisions aimed at reducing vulnerability may even lead to unintended consequences that in fact increase vulnerability, as has often occurred in complex technological systems (Perrow, 1999).

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 (cf. Torgerson, 1985). 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, like the extreme events themselves, 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 (e.g., Slovic, 1993). 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 (e.g., Simon, 1983).

Decision processes, that is, 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 (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 better decisions?), a comprehensive, practical research agenda can emerge (e.g., see NRC, 1999). Such an agenda is not an alternative to disciplinary research, but a complement: It represents a framework for problem choice, integration, and application.

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 are particularly important: modeling, predictions, integrative observation, and acquired (experiential) knowledge. They permit disparate scientific disciplines to work together; and they are the heart of a continual feedback process that can link science to decision making, and decision making to vulnerability reduction.

Modeling

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

There are two types of models, consolidative and exploratory (Banks, 1993). 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. Consolidative 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 selloffs; social, political, and environmental conditions leading 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 the Federal Emergency Management Agency'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 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 (FEMA, 2001).

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 (Geller et al., 1997). 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) predictable with known reliability under many circumstances.

2. *Predictable and not understandable.* Time sequence data and other empirical data may render some extreme events generally predictable even if they are not well understood. For example, the course of AIDS in Africa was predicted over a decade in advance, even though the mechanisms of disease transmission were not well elaborated (Joyce, 1986; Kingman, 1988).

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 reliable 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, climate, 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 the 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 (Lemos et al., in review). The problem was that the science was aimed at good predictions, rather than good decisions.

The role of predictions in addressing extreme events is complex. The quest for predictive accuracy may or may or may not be a good use of scientific resources, and it may or may not have a beneficial effect on decision making, depending on a wide range of factors. In general, predictions can act as an integrative mechanism for linking science to decision making if predictive science is carried out in light of the following (Sarewitz et al., 2000).

1. Predictions must be generated primarily with the needs of the user in mind. Stakeholders and scientists should 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 comprehend 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).

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 gauge 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 may be realized by combining information from advanced observational technologies with empirically derived criteria for recognizing event precursors (Walsh, 1988; Raeburn, 1999; U.S. Agency for International Development, 2001).

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 (or be adapted to 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 comparatively minor) extreme event (G. Martone, pers. commun., June 2000). During the 1997 Red River Flood in North Dakota, copious observational data about river conditions were available, but weather forecasters and local decision makers failed to appreciate uncertainty in the flood predictions, thereby magnifying the scale of the disaster (Pielke, 1999a).

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.

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 (e.g., Cuny and Hill, 1999).

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 (R. Eisner, pers. commun., June 2000). 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 to reduce vulnerability and respond to impacts. However, the appropriate design, role, and application of these integrating mechanisms, including their relations to each other, are far from well understood, and are themselves inherently contextual and dynamic. This means that constant communication between researchers and decision makers is an absolutely essential component of addressing the rising threat of disasters and other extreme events.

Implications for Science Policy: Creating Useable Knowledge

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

The framework we have presented for organizing research on extreme events has significant implications for science policy. Most importantly, in viewing decision processes as the key element of both analysis and action, good decisions emerge as the goal of research, rather than good predictions, good theories, or good models. Good decisions, in turn, are measured by their capacity to reduce vulnerability. The key idea here is that developing effective research agendas to support vulnerability reduction depends critically on understanding the context for decision making, so that appropriate and useable knowledge can be created. This contextual approach demands appropriate ways of thinking about how knowledge is generated and applied (Table 1).

Under this framework, supporting the "best science" according to criteria internal to the research enterprise is an insufficient basis for successful science policy. Policies and institutions organized around advancing traditional disciplines will need to consider additional criteria for designing research programs—most importantly, an understanding of the decision context. Such understanding is not simply a matter of supporting more research on decision-making, although such research may be helpful. Rather, it demands processes that allow decision makers and knowledge creators to better understand one another's needs, capabilities, and limitations. Achieving this understanding 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 may 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 science-and-policy approach to extreme events where such cohabitation could productively take place.

There is no simple, causal relation between "more information" and "better decisions." Indeed, the availability of new information often adds complexity to extreme events or actually changes their

TABLE 1. Components of "Traditional" and "Contextual" Extreme Events Research and Policy Frameworks

Component	Traditional framework	Contextual extreme events framework
Organizational norm	Disciplinary by phenomenon	Integrative; contextual
Institutional norm	Science isolated from decision processes	"Living with users"
View of disasters	Discrete events; isolatable phenomena	Interconnected events; contextual and relational phenomena
View of "extremeness"	Absolute magnitudes	Defined by context
View of "eventness"	Absolute place in time and space	Defined by context
View of vulnerability	A system condition	A dynamic interface
Role of decisions	Translation of knowledge into action. Decisions as external to science agenda	Integrative feedback between knowledge and action Understanding decisions as central research question
Integration of knowledge	Occurs after knowledge creation; prior to decision making	Integral with knowledge creation and decision making
Approach to prediction	Determine time and place of occurrence; a numerical product	Assess predictability; understand impacts of a decision product
Sources of knowledge	Scientific research	Scientific research, experience, intuition, heuristics
Process model	More information means better decisions	The value of information is highly contextual. Understanding the context helps determine what information is needed

course. For example, the media often play a formative role in both bringing public attention to, and influencing the evolution of, extreme events. In an open society, the relation between researchers and decision makers can be made enormously more complex by media coverage of, say, a predicted extreme event (e.g., Y2K). Intervention by the United States in Kosovo (and the subsequent Serbian expulsion of the Kosovars) was arguably precipitated by media coverage. As another example, predictions of extreme events can have both costs and benefits. In Grand Forks, North Dakota, a scientifically "good" flood crest prediction in 1997 provoked disaster management decisions that led to damages that were arguably greater than they would have been under conditions of greater decision uncertainty (Pielke, 1999a). Increasingly accurate predictions of hurricane landfalls in the United States have been accompanied by increasing lengths of shoreline evacuated—precisely the opposite effect of what was expected and intended (Pielke, 1999b). Understanding such complexities is an essential component in the broader process of creating useable knowledge.

The National Weather Service, the volcano and earthquake hazards programs at the U.S. Geological Survey (USGS), and the U.S. network of agricultural extension services represent reasonably successful examples of how scientific research efforts can be organized to match science agendas to the needs of decision makers (Rasmussen, 1989; Sarewitz et al., 2000; NRC, 2001). While each of these examples displays distinct organizational attributes, they are similar in one crucial way: a commitment to communication between information providers and information users. These relationships may take years or decades to become strong; as part of this process, scientific agendas and decision contexts can co-evolve in response to mutual understanding. The evolution of USGS hazards research, from a program focused on advancing scientific knowledge to one with a significant capability to support decision processes, reflects such a gradual co-evolution (NRC, 2001).

Summary

Changing social and environmental conditions on the Pacific rim challenge the scientific community to provide knowledge and insight that can improve the ability of decision makers to reduce vulnerability to disasters. While integrated approaches to hazard mitigation have evolved in various nations and regions, designing scientific research agendas that are compatible with public policy needs remains a significant obstacle. Here we have presented a framework for thinking about this problem in a broadly systemic way. This framework is built on two observations: that disasters and other extreme events are themselves contextual and relational, and that decision processes are the fundamental way in which new techniques for integrating and communicating knowledge can be linked to reduction of vulnerability. By placing disasters within this framework, different types of organizational relations, problem definitions, and research priorities emerge. If science can respond to this more integrative context, its public value may be considerably enhanced.

Acknowledgments

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APPENDIX. List of Participants in Workshop on Extreme Events

Anderson, Aaron	National Center for Atmospheric Research
Atallah, Mikhail	Purdue University
Avery, Susan	University of Colorado
Bostrom, Ann	National Science Foundation
Brown, James	University of New Mexico
Brunner, Ronald	University of Colorado
Cohn, Tim	United States Geological Survey
Colvin, Peter	Pacific Disaster Center
Cornell, Allin	Stanford University
Davidson, Margaret	National Oceanic and Atmospheric Administration
Downton, Mary	National Center for Atmospheric Research
Eisner, Richard	California Office of Emergency Services
Gilbert, Lewis	Columbia University
Harriss, Robert	National Center for Atmospheric Research
Heiken, Grant	Los Alamos National Laboratory
Hunsdorfer, Tim	National Center for Atmospheric Research
Jamieson, Dale	Carleton College
Krantz, David	Columbia University
Kunreuther, Howard	Wharton School of Economics
Lahsen, Myanna	National Center for Atmospheric Research
Landsea, Chris	National Oceanic and Atmospheric Administration
Lemos, Maria	University of Arizona
Lerner-Lam, Arthur	Columbia University
Martone, Gerald	International Rescue Committee
Miller, Kathy	National Center for Atmospheric Research
Mitchell, Ken	Rutgers University
Moore, Chester	Centers for Disease Control and Prevention
Morrow, Betty	Florida International University
Morse, Rebecca	National Center for Atmospheric Research
Murdy, Edward	National Science Foundation
Myers, Mary Fran	University of Colorado
Nelson, Priscilla	National Science Foundation
Norman, Andrew	MAYA Design Group
Parrish, Judith	University of Arizona
Perrow, Charles	Yale University
Pielke, Roger	Colorado State University
Platt, Rutherford	University of Massachusetts
Rundle, John	University of Colorado
Scheiner, Sam	National Science Foundation
Shuchman, Robert	ERIM International
Stanley, Ellis	City of Los Angeles
Stephens, Pam	National Science Foundation
Valette-Silver, Natalie	National Oceanic and Atmospheric Administration
Wallace, Al	National Science Foundation
Walter, Martin	University of Colorado
Wesson, Rob	U.S. Geological Survey
Whitcomb, Jim	National Science Foundation
Wilhelmi, Olga	National Center for Atmospheric Research