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**Environmental Science for Extreme Events**

A ‘Concepts’ article for

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By

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Rare extreme events are notoriously hard to manage. Yet in our rapidly changing and interconnected world, the impact of environmental hazards is increasing, jeopardizing human security and impeding human development ([MillenniumEcosystemAssessment 2005](#_ENREF_21), [Pauchauri and Reisinger 2007](#_ENREF_23)). Environmental hazard and disaster losses in the U.S. are increasing ([Cutter and Emrich 2005](#_ENREF_8)) and similar trends are observed globally ([MillenniumEcosystemAssessment 2005](#_ENREF_21)). Climate change can increase the probability of stronger storms ([Emanuel 2005](#_ENREF_10), [Webster et al. 2005](#_ENREF_29), [Min et al. 2011](#_ENREF_22)). Regional environmental change increases the probability of disease emergence ([Keesing et al. 2010](#_ENREF_14)). No one foresaw that changes in animal feeding practices would lead to emergence of a variant form of Creutzfeld-Jakob disease ([d'Aignaux et al. 2001](#_ENREF_9)). In a highly engineered and increasingly crowded world, disasters are compounded, as when the Honshu earthquake of 2011 triggered a tsunami that breached seawalls, destroyed towns, killed thousands of people, disrupted supply chains for energy and food, and severely damaged nuclear power stations.

Formation of effective institutions and policies for extreme environmental hazards is complicated by the fact that perceptions of evolving risks tend to be heavily biased. There are many needs for research to improve understanding and management of extreme environmental events, and we describe some of these in this paper. We suggest that management of extreme events related to global change should be addressed through (1) exposing vulnerabilities and discovering new response options, (2) increasing opportunities to take appropriate action and (3) building resilience to unpredictable events. These approaches represent an important paradigm shift, from a world-view that strives for stability and control, to a more pragmatic perspective aimed at building resilience and adaptive capacity to cope with accelerating global change, increasing uncertainty and inevitable surprise.

**Intuition Fails at the Tails**

So far, the tallest players in the U.S. National Basketball Association have been 231 cm (Manute Bol and Georghe Mureşan are tied for this record). The height of the future player who breaks this record is much more likely to be 232 cm than 300 cm. For human height increments, expected values decline quickly as they fall farther from the mean. Such probability distributions are called thin-tailed. The expected value of an extreme event above a threshold in thin-tailed distributions is only a small amount greater than the threshold itself. Tail thickness can be diagnosed by plotting the mean excess (expected increment above a threshold) versus the threshold (Fig. 1). The mean excess is inversely related to the threshold in thin-tailed distributions (Fig. 1A). Such relationships hold for many distributions and accord with intuition about extreme events – a new record is only slightly larger than the old record.

However, for many variables the mean excess increases as the threshold increases (Fig. 1B). Such distributions are called thick-tailed. This phenomenon was first noticed by the economist Vilfredo Pareto in 1906, with regard to the distribution of wealth in Italy, and it led to his name being applied to the Pareto distribution. Thick tails also characterize the impacts of environmental hazards such as floods, earthquakes, landslides, and wildfires ([Malamud 2004](#_ENREF_19), [Kousky and Cooke 2010](#_ENREF_15)). For thick tailed distributions, intuition fails because the next extreme event may be vastly greater in impact than the previously-observed record event. Recent experience is a poor guide to the severity of future events.

For any distribution, our knowledge of the tail is necessarily limited; by definition the tail has low probability and extreme values occur only rarely in the data. For thin-tailed distributions this problem is of small consequence, because we know that the expected value above a threshold is not much larger than the threshold itself. In contrast, for thick-tailed distributions the expected value above a threshold is substantially larger than the threshold, and in addition it is not well known. This profound uncertainty makes even rational responses difficult, and makes it easier for irrational responses to take hold.

**Under- and Overreactions**

Fundamental psychological characteristics of the human mind hamper our ability to deal with extreme events (Fig. 2) and cause people to under- or overreact ([Meyer 2010](#_ENREF_20)). Denial or under-reactions arise when individuals are unfamiliar with the threat or they choose to ignore it (under-reaction type 1, Fig. 2). If tail events are quite rare, and people pay most attention to more recent events, then people tend to under-react. In these cases, low-level risks are effectively set to zero, as has happened at various times with hazards such as second-hand smoke, chlorinated hydrocarbons, nuclear winter and climate change ([Sunstein 2002](#_ENREF_25)). Extremely common and familiar risks may also be underestimated even though they are potentially catastrophic ([Kunreuther and Useem 2010](#_ENREF_18)). For example we are overconfident in our private ability to control public risks (under-reaction type 2, Fig 2). Many individuals prefer to drive than fly, even though driving is more dangerous than commercial air travel.

While we are most concerned about under-reaction, people can overreact to risks that are sensational and highly publicized (Fig. 2) ([Sunstein 2002](#_ENREF_25)). Terrorism is a familiar example. At a more personal level, we often purchase maintenance plans for common electronic equipment even though breakdowns are so rare that self-insurance is more cost-effective.

These biases in risk perception, which are well-studied for individuals, can be amplified by group dynamics ([Scheffer et al. 2003](#_ENREF_24)). Inevitably such biases drive democratic decision making. Under-reactions put people in danger; overreactions divert resources away from problems more deserving of attention. The solution for irrational risk perception is institutional arrangements that account for biases, as well as research and education that expose and reduce biases in risk perception.

**Research Gaps in Environmental Science**

More work is needed in interdisciplinary environmental science to address thick-tailed distributions of environmental catastrophes. Such catastrophes are intrinsically human-environmental phenomena, involving physical, biological and social factors. Many relevant results come from the literature on management of thick-tailed risks in actuarial science and finance, yet the key ideas are not well known in other fields, including environmental science.

Univariate extreme events are hard to study because they are rare, and multiple correlated risks are more difficult still. Even mildly correlated risks are amplified in the tails of multivariate thick-tailed distributions. Yet measurement and estimation of upper tail dependence is often poorly understood, and mistakes in analysis are quite dangerous in practice ([Embrechts et al. 2002](#_ENREF_11)). In a multivariate thin-tailed distribution, the correlations of the most extreme events are small (Fig. 3A). In contrast, the correlations of the most extreme events in a multivariate thick-tailed distribution are large (Fig. 3B). In practice this means that multiple extreme events or “multiple whammies” are surprisingly common in multivariate extreme value distributions ([Embrechts et al. 2002](#_ENREF_11)). Strategies for managing thick-tailed environmental risks should plan for the possibility that several extreme events will tend to happen together, as occurred in the Honshu earthquake of 2011. Chains of extreme events seem to be more common in our highly connected world and problems of managing them are likely to intensify in the future ([Walker et al. 2009](#_ENREF_27)).

Microcorrelations are a different statistical phenomenon that can cause risk management strategies to fail. Microcorrelations are real, but small and undetected, correlations in the response of sites to environmental variability such as floods or droughts. When sites are aggregated to regional or continental extents, microcorrelations accumulate to form strongly correlated responses at the larger spatial extent ([Cooke and Kousky 2010](#_ENREF_7)). Fig. 4 shows a simple example. An insurance strategy that spread risk among sites would seem safe, because a disaster at one site is not likely to be associated with disasters at multiple sites (Fig. 4A). In this context insurance could be monetary insurance, or it could be a conservation strategy such as maintaining a network of refugia for a rare species. An insurance strategy that spreads risk among regions of 100 sites must contend with surprisingly high correlations among regions caused by the aggregation of microcorrelations among sites (Fig. 4B). Thus a disaster in one region is likely to be accompanied by disasters in other regions at the same time. The cost of monetary insurance must therefore be adjusted upward to accommodate the risk of simultaneous disaster in many regions. In the case of conservation “insurance”, managers should seek to break up the correlations by including some refugia that are environmentally independent of the others. In an increasingly connected world, larger disasters are more likely to co-occur and thereby stress the resources of insurers, managers and governments.

Ecological monitoring, modeling and assessment need to improve databases and understanding related to extreme ecological events. While the study of disturbance is well-developed in ecology, ecological disturbance regimes are changing rapidly ([Turner 2010](#_ENREF_26)). Altered frequency and magnitude of fires, floods, droughts and other massive ecosystem events have significant consequences for living resources such as forests, freshwater and food production. Record temperatures, drought and wildfires burned away much of Russia's wheat harvest in 2010. Russian exports halted, commodity prices rose to record levels by December 2010, and by January 2011 food prices were among the triggers for Tunisia's unrest as well as for riots across much of northern Africa, including Egypt, a country that depends heavily on Russian grain ([Fraser and Rimas 2011](#_ENREF_12)). There is urgent need to understand both the ecological and social implications of changing ecological disturbance regimes ([Turner 2010](#_ENREF_26)).

Statistical phenomena such as extreme-value tail dependencies and aggregated microcorrelations should be incorporated much more broadly into environmental science and planning. Both phenomena are difficult to measure and understand, and thereby expose the need for approaches to management and decisions that account for ambiguity and uncertainty about uncertainties (Polasky et al. in review). Moreover, there is fundamental need for better understanding of the physical, biological and social processes that generate thick-tailed environmental risks.

Important governance issues are raised by the difficulty of estimating and building intuition about thick-tailed risks. For example, countries with high greenhouse gas emissions could be accused of imposing thick-tailed climate damage risks to other countries. Ideal governance structures would internalize these costs for the countries that cause the costs. Poor quantification of these externalities, however, makes it difficult to design policies that internalize them. In the case of the Mississippi River basin of North America, land use actions and water management structures throughout the basin have contributed to disaster losses from flooding and storm surges ([Kousky and Zeckhauser 2006](#_ENREF_16)). Policy solutions to regional patterns of malpractice are quite challenging because of the difficulty of assigning responsibility as well as the collective action problems caused by so many injured and injury-causing parties ([Kousky and Zeckhauser 2006](#_ENREF_16)).

Although there is a large literature on rules to assign liability in damage cases, work is needed on the design of legal liability frameworks for thick-tailed environmental damages ([Avraham 2006](#_ENREF_2)). Research on thick-tailed environmental risk could be integrated with research on policy design to develop incentive schemes that efficiently mitigate thick-tailed environmental risk. For example, what sorts of rules will effectively motivate those who build levees and fill wetlands upstream to reduce thick-tailed damages to downstream interests?

**Preparing for Extremes**

Turning from research to management, how can society’s capacity to address extreme environmental events be expanded? We suggest three major needs.

Expose vulnerabilities and discover new response options: To better cope with future risks, it is important to recognize the magnitude and impact of extreme events and to incorporate them into real-world decisions. For example, global assessments can use scenario planning to widen the scope of potential events that are considered, including rare shocks ([MillenniumEcosystemAssessment 2005](#_ENREF_21), [Pauchauri and Reisinger 2007](#_ENREF_23)). Vulnerabilities can be exposed through improved communication and awareness, better forecasting, learning from experiences elsewhere, and disaster preparedness programs. In many parts of the world, failure to reduce social vulnerabilities amplifies risk more than escalation of physical hazards does ([WorldBank 2010](#_ENREF_31)).

Growing awareness of antibiotic resistance is leading to more militant surveillance and countermeasures, for example. In 2010, genomic surveys of Delhi’s water supply revealed widespread distribution of the NDM1 gene, which confers resistance to powerful antibiotics normally reserved to treat highly resistant strains of bacteria ([Kumarasamy et al. 2010](#_ENREF_17), [Walsh et al. 2011](#_ENREF_28)). The gene occurs in free-living freshwater bacteria that cause cholera and dysentery and are easily passed from person to person. The infection traveled to England in patients who visited India for medical treatment and cosmetic surgery ([Kumarasamy et al. 2010](#_ENREF_17))(Roberts, M., BBC News Health, 6 April 2011, <http://www.bbc.co.uk/news/health-12975693>). Expanded treatment of Delhi’s drinking water and vigilance by health tourists may slow the spread of the bacteria to humans. However, stopping the misuse of antibiotics and invention of new antimicrobial agents are crucial public health priorities ([Conly 2010](#_ENREF_6)).

Research on extreme events is urgently required to expose emerging vulnerabilities or opportunities, and thereby alert decision makers of the need to consider responses to new kinds of risks. Crises and surprises, often viewed solely as negative threats, can potentially afford opportunities for constructive change and innovation if they are noticed soon enough.

Increase opportunities to take action: Many private and public actions are used to manage thick-tailed risk. Among the simplest solutions to the problem of poor risk perception is to require people to buy insurance. The insurance company has a strong incentive to analyze the risk properly. However, as shown above, many environmental risks are very difficult to measure or manage.

Institutions can improve their capacity to cope with thick-tailed hazard distributions by learning from successes and failures. Tradeoffs between precaution and learning underlie future policy options for thick-tailed events. The precautionary principle leads to policies that avoid serious or irreversible harm, without a clear demonstration that such actions are absolutely necessary. However, the conservatism associated with the precautionary principle can prevent learning about thick-tailed processes or discovering new vulnerabilities or response options ([Carpenter 2003](#_ENREF_5)) . Foregone learning is part of the cost of precaution, which must be weighed against highly uncertain future benefits that could be large if realized.

Institutions have a mixed record in regard to implementing precautionary policies and reacting to global change. For example, the Montreal Protocol was adopted before “peer-reviewed scientific data [had] incontestably [linked] chlorofluorocarbons with ozone-layer depletion and the Antarctic ‘ozone hole’” ([Benedick 1990](#_ENREF_3)). The International Health Regulations, long known to be grossly inadequate, were revised substantially in the wake of the SARS outbreak. The global response to the emergence of H1N1 pandemic influenza, while not perfect, was also improved by revising regulations already in place ([Wilson et al. 2010](#_ENREF_30)) .

Trans-boundary governance of global climate engineering will be a major issue in coming years ([Bierman et al. 2010](#_ENREF_4)). Who should decide whether new technologies should be deployed, when the consequences of using them are global and uncertain? Parties to the Convention on Biodiversity and the London Convention on the Oceans both cautioned against ocean fertilization experiments, and yet Germany and India proceeded with one anyway. Clearly there is urgent need for new, multi-scale institutions with responsibility for collective and equitable action for coping with thick-tail events and global change ([Walker et al. 2009](#_ENREF_27), [Galaz et al. 2010](#_ENREF_13)).

Build resilience to thick-tailed events: Perhaps the most important step is to recognize that thick-tailed environmental risks are more common than our intuition suggests. Clusters of extreme shocks are unexpectedly common. Local correlations that are too small to measure can aggregate to costly simultaneous shocks in a highly connected world. Thus the next extreme impact will not be just a little worse than we have seen so far. Instead it will be many times worse than the worst event so far. We should expect that, and adjust our plans accordingly.

Many steps can be taken in advance to cope with surprise when it happens. The attributes that confer social and ecological resilience to shocks are often unrecognized, and they may be eroded or lost over time unless they are actively fostered and managed. Increased awareness and communication, improved education and social capital, leadership, and multi-scale governance are critical elements in reducing vulnerability and building resilience to shocks ([Adger et al. 2005](#_ENREF_1)).

In building resilience to environmental disasters, the World Economic Forum ([2008](#_ENREF_32)) identified four areas of opportunity for private-sector engagement: monitoring hazards and communicating risk (through early warning systems, for example), social-physical strengthening (such as protection of power, water and sanitation plants, diversification of supply chains, and establishment of ecological buffers), sharing of financial risk (using instruments such as weather derivatives or catastrophe bonds), and disaster preparedness (e.g. training or establishing reserves of pharmaceuticals). Regarding the role of government in environmental disasters, the World Bank ([2010](#_ENREF_31)) is focusing specifically on four policy needs: (1) Making information about environmental disaster risk more easily accessible. (2) Using land and housing markets to induce people to locate in appropriate areas and take preventive measures. (3) Providing adequate infrastructure and public services to reduce vulnerabilities. (4) Building institutions that permit public oversight of disaster preparedness and disaster response.

**Conclusion**

Humanity has always faced environmental hazards. However, current global changes appear to be increasing the number of kinds, severity, and co-occurrence of environmental hazards. Damage distributions of these hazards are thick-tailed, meaning that future shocks substantially exceed current experience and are highly uncertain. This deep uncertainty is a challenge for management even when beliefs are rational; more so when irrational beliefs take hold. The potential divergence of rational and irrational responses in a world of escalating risk makes research on thick-tailed risks even more valuable and urgent. Management of expanding environmental hazards requires confrontation of irrationality through data and discussion, changes in institutions for managing risks, and preparation for surprise through policies that build resilience.

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