Risk, Governance and Society

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Risk Analysis of Natural Hazards

Interdisciplinary Challenges and Integrated Solutions

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Chapter 1
Risk Analysis of Natural Hazards: Interdisciplinary Challenges and Integrated Solutions

Paolo Gardoni, Colleen Murphy, and Arden Rowell

Abstract Natural hazards can have a devastating impact on society. They cause billions of dollars of damage each year, kill thousands, and render millions homeless, and their frequency and severity are expected to increase with climate change. Although the source of damage from natural hazards may appear to be "natural," in fact it results from complex interactions between the natural environment, human decisions about the built environment, and social vulnerability. This volume brings together leading minds in engineering, science, philosophy, law, and the social sciences to develop a deeper understanding of the interdisciplinary challenges involved in the mitigation of natural hazards.

Parts I and II of this volume explore risk assessment, first by providing an overview of the interdisciplinary interactions involved in the assessment of natural hazards, and then by exploring the particular impacts of climate change on natural hazard assessment. Part III discusses the theoretical frameworks for the evaluation of natural hazards. Finally, Parts IV and V address the risk management of natural hazards: Part IV provides an overview of the interdisciplinary interactions underlying natural hazard management, and Part V explores decision frameworks that can help decision makers integrate and respond to the complex relationships among natural events, the built environment, and human behavior.

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1.1 Introduction

Natural hazards cause billions of dollars of damage each year, kill thousands, and render millions homeless, and their frequency and severity are only expected to increase with climate change. Although the source of damage from natural hazards may appear to be "natural," in fact it results from complex interactions between the natural environment, human decisions about the built environment, and social vulnerability. The risk associated with natural hazards arises when the interaction of natural events, the built and modified natural environments and social vulnerability creates a possibility for disaster. The impact of natural hazards depends importantly upon the choices individuals and communities make in the construction of the built environment, such as whether individuals will be permitted to live in areas vulnerable to flooding or hurricanes, and what level of safety is demanded of buildings and bridges. It also depends upon differences in vulnerability—the predisposition to loss or damage—which is influenced by individual, household, and societal assets and social protections.

To illustrate, consider the impact of earthquakes. In 2010, a magnitude 7.0 earthquake in Haiti occurred. Much of Haiti's capital city of Port-au-Prince was reduced to rubble. Hundreds of thousands of people died, hundreds of thousands more were injured, and a million were left homeless. The same year, an 8.8-magnitude earthquake struck Chile—a natural event that released over 500 times the energy at its epicenter than the Haitian quake and ranks in the top ten most energetic earthquakes ever recorded. Yet, the death toll from the Chilean quake was three orders of magnitude lower than in Haiti—hundreds rather than hundreds of thousands. What was different about Chile? Just to mention a few differences, Chile, unlike Haiti, had a robust (and enforced) set of building codes that was designed to be resilient to seismic events—meaning that individual structures were less likely to collapse, and the key infrastructures like hospitals could continue to operate after the quake. Chileans, unlike Haitians, were accustomed to earthquakes and had a set of social norms, habits, and supports that allowed for an organized response to the natural event itself. And in Chile, unlike in Haiti, the earthquake itself occurred some distance from the primary areas where people had chosen to build their homes. Both the Chilean and Haitian earthquakes were disasters with tragic outcomes, significant social impact, and wide-ranging economic effects. What the comparison illustrates, however, is that physical processes alone cannot predict or prevent destruction from natural hazards. To understand what makes natural events into disasters, it is critical to understand how those events interact with the built environment, and with the social behaviors of people who act within that environment.

Successful understanding, management, and mitigation of risks from natural hazards require the technical expertise of engineers and scientists; the legal and policy expertise of legal scholars; the ethical expertise of philosophers; and the cultural, psychological, political, and economic expertise of social scientists. The interdisciplinary field of risk analysis is a promising home for the discussions necessary to manage the complex interactions between the physical, the ethical, and the social that combine into natural hazards.

The general study of risk initially concentrated on a relatively narrow question related to the odds of winning games of chance. The book by Girolamo Cardano (1500–1571) "*Liber de Ludo Aleae* (*Book on Games of Chance*)" is possibly the first systematic attempt to formulate mathematical principles for risk analysis. After him and starting with the Renaissance, the theoretical foundations of the modern theory of risk analysis was laid through the contribution of mathematicians like Pascal and Fermat in the 1600s, Leibniz, Bernoulli, de Moivre and Bayes in the 1700s, Galton in the 1800s, and Markowitz in the 1900s. In more recent years, the field of risk analysis has expanded, benefitting from significant contributions in a number of fields beyond mathematics including engineering, philosophy, law, and psychology. However, much work continues to be done by scholars investigating risk from the perspective of a single discipline while communities face interdisciplinary challenges that call for integrated solutions. Building on a highly successful international working conference, this volume brings together leading minds in engineering, science, philosophy, law, and the social sciences to develop a deeper understanding of the interdisciplinary challenges involved in the mitigation of natural hazards.

Risk analysis is often divided into three types of inquiry: risk assessment (the quantification of the levels of risk associated with particular hazards), risk evaluation (the formulation of value judgment about assessed risks), and risk management (the decision process on whether and how to act upon the information from the risk evaluation). The structure of this volume echoes these categorizations. It begins in Parts I and II by exploring risk assessment, first by providing an overview of the interdisciplinary interactions involved in the assessment of natural hazards, and then by exploring the particular impacts of climate change on natural hazard assessment. Part III discusses the theoretical frameworks for the evaluation of natural hazards. Finally, Parts IV and V address the risk management of natural hazards: Part IV provides an overview of the interdisciplinary interactions underlying natural hazard management, and Part V explores decision frameworks that can help decision makers integrate and respond to the complex relationships among natural events, the built environment, and human behavior.

Part I provides an overview of current interdisciplinary issues involved in risk assessment. One obstacle to effective mitigation strategies is the divergence between risk assessments by risk experts and the lay public. In "Risk Assessment and Social Choice," philosopher Tim McCarthy and sociologist Noreen Sugrue argue that there is no reason to categorically reject either type of risk assessment. Instead, competing risk assessments point to different competencies of and diverse normative constraints endorsed by experts and the lay public, respectively. They propose a framework for amalgamating competing assessments of social interventions, actions taken by actors outside a community designed to solve a given social problem. Through a "spiderweb" diagram competing risk preferences can be ranked along various dimensions, which allows elements of both groups to be represented and respected. After sketching the framework, McCarthy and Sugrue apply it to two different cases.

Risk assessments by both the public and risk experts are shaped by how those experts implicitly conceptualize nature, technology, and vulnerability. In "Vulnerability to Natural Hazards: Philosophical Reflections on the Social and Cultural Dimensions of Natural Disaster Risk," philosopher Mark Coecklebergh problematizes discussion of "natural" disasters, insofar as both the causes of disasters and impact of disasters are, as noted above, shaped by human choices in policy, infrastructure, and the distribution of goods within a community. Coeckelbergh argues that non-modern viewpoints on risks from natural disasters offer fruitful resources for understanding the limits of technical solutions to natural hazards and the limits of our ability to completely manage and control such hazards.

Finally, in "Discount Rates and Infrastructure Safety: Implications of the New Economic Learning," law professor Daniel Farber explores the relationship between recent economic work on discounting—a tool used by economists to make tradeoffs through time—and disaster policy. A recent and emerging consensus among economists would apply declining discount rates over time: a declining discount rate offers a long-term hedge against uncertainty regarding economic growth. Because discounting is the flipside of compound interest, a declining discount rate has the overall impact of *increasing* the resources allocated to policies that reduce distant-future harm. Farber argues that this new approach to discounting has important and distinctive implication for disaster policy, because natural hazards tend to be spread sparsely over time, such that they tend—at any particular time point—to be most likely to occur in the "distant future." Farber then contrasts the impacts of a declining discount rate with current U.S. practice, which is still to use a fixed discount rate when comparing and analyzing possible policy impacts. He concludes that the new generation of economic analysis, which supports the use of declining discount rates, suggests that existing practice leads society to underinvest in infrastructure resiliency and in other projects that might reduce total losses from natural hazards.

Part II of the volume focuses on future challenges in risk assessment and, in particular, those brought by climate change. In his chapter titled: "Setting the Stage for Risk Management: Severe Weather Under a Changing Climate (Chap. 5)," atmospheric science professor Donald J. Wuebbles summarizes and critically evaluates the latest scientific findings on climate change. Particular emphasis of the chapter is on the latest trends and future projections, which are based on different possible scenarios. Wuebbles discusses the issues related to the uncertainties associated with predictions of future climate changes, and some of the implications of climate change on society. This chapter also emphasizes that climate change is likely to continue to increase the frequency and severity of extreme weather events.

In "Climate Change and Natural Hazards," philosophy professor Doug MacLean discusses the moral dimensions of climate change. He highlights the ways that the temporal and spatial aspects of climate change complicate ethical thinking. MacLean argues that together these aspects produce a unique moral dilemma: the challenge is to identify a way of framing the problem posed by climate change that makes both justice and intergenerational concern for posterity relevant at the same time. Part of the challenge in achieving this is that, MacLean argues, the values of justice and intergenerational concern pull in competing directions.

Civil infrastructure facilities are essential elements for the well-being of a society. Natural events like hurricanes and cyclones, tornadoes, earthquakes, and floods subject civil infrastructure facilities to extreme loads that could cause their failure with very significant societal impacts. Civil engineering professor Bruce Ellingwood and graduate student Ji Yun Lee critically investigate a number of issues that need to be considered in the life-cycle assessment of such infrastructures. Issues considered include the effects of climate change (in particular on the likelihood and magnitude of some extreme natural events), the role of the interdependency among facilities, the implications of population growth (particularly in coastal regions) and infrastructure development, and the consequences of the longer service life of many civil infrastructure facilities with respect to traditional service lives going well beyond typical budget cycles and charge time of decision makers.

Civil engineering professor David Rosowsky and graduate students Lauren Mudd and Christopher Letchford then investigate the impact of climate change on the likelihood and severity of hurricanes in the Northeastern Coastline of the U.S. in their chapter “Assessing climate Change Impact on the US East Coast Hurricane Hazard (Chap. 8).” They considered multiple climate change scenarios and models to construct probabilistic models of different hurricane characteristics (like frequency, genesis location, and track behavior) and of measures of hurricane intensity (e.g., wind speed and rainfall.) The models are then used to predict the joint likelihood of wind speed intensity, spatial extent/storm size, and rainfall rate. The chapter concludes with a discussion of the implication of climate changes on design provisions for civil structures and infrastructure.

Part III focuses on risk evaluation and in particular on possible theoretical frameworks for risk evaluation. Philosophy professor Adam Hosein in his chapter “Deontology and Natural Hazards (Chap. 9)” sketches an alternative to the widely used cost-benefit approach to policy choice and decision-making. Hosein’s starting point is important: widely recognized moral distinctions that cost-benefit analysis does not take into account. One such distinction is the difference between allowing a harm to occur and doing an action that leads to harm. Hosein’s deontological approach takes into account such distinctions.

Philosophy professor Sven Ove Hansson concentrates on traditional probabilistic risk assessment and identifies important limitations with it in his chapter “Managing Risks of the Unknown (Chap. 10).” First, he argues, the appropriate way to treat risks for which there can be no meaningful probability assigned must be developed. Second, ethically salient matters such as equity, consent, and voluntariness must be incorporated into risk evaluation. Hansson presents three frameworks for dealing with these issues: possibility analysis, three-party model, and hypothetical retrospection.

Finally, risk analysts Louis Anthony (Tony) Cox, Jr. and Emeline D. Cox in their chapter, "Intergenerational Justice in Resilience Investments with Uncertain Future Preferences and Resources (Chap. 11)," build on themes in the chapters by Hosein and Hansson (Chaps. 9 and 10). Their central question is: "How much should each generation invest in building resilient infrastructure to protect against possible future natural disasters given uncertainty about the preferences, resources, and capacities of future generations?" Cox and Cox discuss a number of different frameworks for dealing with this question, including optimal economic growth models, behavioral economics, and the Rawlsian moral framework. Rather than choosing one framework over the others, Cox and Cox argue that each framework has important insights. Jointly the frameworks highlight the fact that standards of success in investing in resilient infrastructure depend on a rich understanding of human nature and cooperation over time, what is needed to maintain such cooperation over time, the goals of building a resilient infrastructure, and the trade-offs any choice entails.

Part IV focuses on risk management from an interdisciplinary perspective. In "War Rhetoric and Disaster Transparency," law professors Lisa Grow Sun and RonNell Anderson Jones deconstruct the use of war and national security rhetoric to discuss disasters and disaster policy. They argue that rhetorical comparisons of war and disasters—and particularly disaster aftermath—can lead policymakers to select policies that are insensitive to a critical distinction between war and disaster: the existence of a thinking enemy. Sun and Jones prescribe a careful analytical disaggregation of dissimilar forms of emergencies and encourage policymakers to systematically interrogate the assumptions underlying how they choose to prepare for and respond to emergencies.

Government decision-making has historically involved the general public to a different degree. Catastrophist Gordon Woo, in his chapter titled "Participatory Decision Making on Hazard Warnings (Chap. 13)" argues that there are a number of advantages of citizen participation in government decision-making. However, citizens' participation also comes with some challenges especially when dealing with technical or scientific matters of which citizens might not have sufficient understanding and when individual perceptions (like the perception of risk) might lead to irrational decisions. Woo discussed the challenges of public participation and offers some strategies on how they could be overcome.

In "The Natech: Right-to-Know as Space-Time," law professor Gregg Macey explores the legal implications of so-called "natech events:" disasters that occur at the interface of natural hazards and technology, as when an earthquake triggers a chemical spill. He argues that natechs present technical and policy challenges that are importantly different from the types of acute, rare, "worst-case scenario" events on which decision makers often focus. In particular, Macey warns that natechs tend to be geographically dispersed and temporally discontinuous and that traditional approaches to managing disaster risk are likely to mismanage the sorts of cumulative impacts that can cause natech disasters. He prescribes response strategies designed to identify, reconstruct, and track cumulative impacts, and urges increased awareness of the mundane infrastructure stressors that tend to increase natech risk.

Finally, Part V of the volume considers decision frameworks for risk management. In “Private Versus Public Insurance for Natural Hazards: Individual Behavior’s Role in Loss Mitigation,” law professor Peter Molk explores the relationship between the legal and institutional structures of insurance markets, and social exposure to catastrophic risks. He argues that the way that insurance is provided (for example, whether private homeowners’ insurance excludes losses from natural hazards) can affect not only the likely cost of public aid in the event of a disaster (a form of what Molk terms “public insurance”) but also individuals’ incentives to prevent or mitigate disaster losses. Molk goes on to describe and analyze the current state of disaster insurance in the United States, focusing particularly on the relationship between traditional private insurance and the federally-provided “public” flood insurance program. He concludes by identifying institutionally-sensitive mechanisms for regulating insurance markets in the United States to incentivize individuals to take risk-reducing behaviors, and thus to reduce overall losses from natural hazards.

Decision-makers, including governmental agencies, often face difficult decisions on the allocation of limited resources to promote the safety of the built environment. In the chapter titled “Risk-informed Decision Framework for the Built Environment: The Incorporation of Epistemic Uncertainty (Chap. 16),” civil engineering professor Eun Jeong Cha and mechanical engineering professor Yan Wang present a framework for risk-informed decision-making that is developed to assist decision makers. Cha and Wang illustrate the proposed framework considering the allocation of resources for a Florida county facing hurricane risk.

Finally Civil engineering professors Mahesh D. Pandey and Neil Lind in their chapter “Societal Perspective in Risk Management: Application of Life-Quality Index (Chap. 17)” focus on the fundamental question, “How safe is safe enough?” The chapter answers this question by striking a balance between the cost associated to measures of risk mitigation and the societal benefits that come from the increased safety. While generally applicable to any engineering infrastructure system, the chapter illustrates the proposed formulation considering the mitigation of risk due to radiation exposure from nuclear power plants.

Throughout the volume, authors refer back to both other authors’ work, and to the interdisciplinary workshop on which this volume was based. We believe that this sort of cross-disciplinary collaboration is critical to the effective mitigation of natural hazards. No single person—and no single discipline—holds the key to reducing the suffering caused by disasters. If we are to find ways to effectively reduce the harm caused by natural events, it must be through cross-disciplinary conversations of the kind that this volume has sought to foster.

Part I
Risk Assessment: An Interdisciplinary Perspective

Chapter 2
Social Choice and the Risks of Intervention

Timothy G. McCarthy and Noreen M. Sugrue

Abstract In this chapter we shall describe and illustrate a framework for assessing risk in the context of social intervention, where by a *social intervention* we mean a set of actions undertaken, typically by an organized ensemble of agents external to a given society, in order to solve a problem identified within that society. We focus on the general problem of amalgamating expert risk assessment and lay risk assessment. A methodology for integrating divergent assessments of risk has at least two virtues: (1) Where these are presumed to differ, this methodology forces the normative and descriptive assumptions underlying the assessments into the open, so that they can be examined; and (2) It provides risk policymakers with a tool for systematically prioritizing the normative constraints underlying the assessments of risk. We argue that there is no need either to rationalize or to condemn the systematic gap in risk analyses that exists between experts and laypersons. Rather, experts and laypersons should be understood as having different competencies, capabilities and normative requirements. Public (and private) risk managers need a systematic approach to managing these distinctive capabilities and requirements—an approach that recognizes the strengths and constraints of each analytical group, and which allows risk managers to integrate all of these factors. In this paper, we are interested in identifying and analyzing how technical experts' risk analyses interact with the lay public's assessments of risk with the principal goal being first to specify formal representations or models of the divergent assessments of risk generated by experts and the lay public and second, to introduce a model for integrating those assessments. We then apply the model to case studies involving natural disasters and health.

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2.1 Introduction

In this paper we shall describe and illustrate a framework for assessing risk in the context of social intervention, where by a *social intervention* we mean a set of actions undertaken, typically by an organized ensemble of agents external to a given society, in order to solve a problem identified within that society. In Sect. 2.2 we will sketch the framework, and in Sect. 2.3 we present two test cases that illustrate both the virtues and the limitations of the framework. These examples concern healthcare outcomes and natural disasters.

This paper focuses on a general problem of amalgamating expert risk assessment and lay risk assessment. A methodology for integrating divergent assessments of risk has at least two virtues: (1) Where these are presumed to differ, this methodology forces the normative and descriptive assumptions underlying the assessments into the open, so that they can be examined; and (2) It provides risk policymakers with a tool for systematically prioritizing the normative constraints underlying the assessments of risk.

The history of public responses to public health crises and natural disasters is replete with examples of systematic divergences between the risk analyses of laypeople and those of technical experts (Slovic 2000, 2010). Empirical literature on decision-making and social choice has traditionally focused on the gaps identified between the expert information and advice and the ability or willingness of laypersons to “listen to the experts” and then act accordingly. Thus, for example, public health experts have argued to the point of exhaustion for the effectiveness and safety to vaccines, in the face of a skeptical subpopulation of the lay public. The characteristic assumption has been that the rational expert focusing on achieving preferred outcomes possess the information relevant to formulating directives that should determine the social choices in question, and that not following the advice or directives of experts requires a special justification. Both popular and specialized accounts of these problems often have a tone of blame or incorporate a call to “correct” the erroneous ways of the lay public.

We argue that there is no need either to rationalize or to condemn the systematic gap in risk analyses that exists between experts and laypersons. Rather, experts and laypersons should be understood as having different competencies, capabilities and normative requirements. Public (and private) risk managers need a systematic approach to managing these distinctive capabilities and requirements—an approach that recognizes the strengths and constraints of each analytical group, and which allows risk managers to integrate all of these factors. In this paper, we are interested in identifying and analyzing how technical experts’ risk analyses interact with the lay public’s assessments of risk with the principal goal being first to specify formal representations or models of the divergent assessments of risk generated by experts and the lay public and second, to introduce a model for integrating those assessments.

The critical mechanism required for this work is a prioritization scheme, which below we formulate using a “spiderweb” diagram (Fig. 2.1). The diagram is one

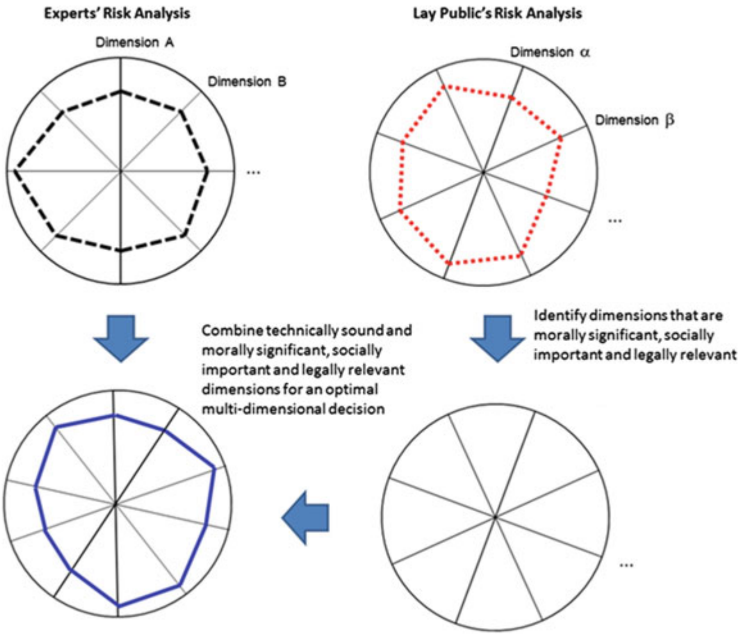

Fig. 2.1 Illustration of multi-dimensional decision-making

type of representation that allows risk managers to recognize the comparative capabilities of the different groups by prioritizing the risk preferences of one group—experts or the lay public—along some parameters, without necessarily allowing the overall preference of either group to dominate. This approach allows decision-makers, including risk managers, to take advantage of the comparative strengths of both experts and the lay public.

2.2 Part I

A key challenge facing risk policymakers is how to integrate divergent risk assessments, particularly between technical experts and the lay public (Moen and Rundmo 2004). This is a significant challenge because policy-makers and elected officials are in the position of accepting and acting upon the expert assessments and recommended solutions which in turn often will often require forcibly changing the life and lifestyle of individuals. This action most certainly will be met with significant resistance by laypersons and in far too many cases will be accompanied by charges of government overreach. It would be an understatement to note that such actions would 'burn' exorbitant amounts of political capital. On the other hand, not following the expert advice and being left to pay the economic, social, and moral prices that accompany bad outcomes because experts were ignored also carries significant costs. The delicate balance of integrating the priorities and assessments of both laypersons and experts is one that has yet to be mastered, in most instances.

It is a commonplace that the public often operates with defective information concerning the empirical background of a choice confronting it. Even when that information is corrected, however, there can remain normative constraints that are at odds with the most direct technical implementation of a proposed expert solution to a social problem. These "local' normative constraints must be incorporated in some way into the overall framework for decision, though it is not obvious how. Thus, for example, the most direct engineering implementation of badly needed infrastructural improvement may infringe upon a socially protected space. The local social preference to protect that space may override at least some feasible implementation of a proposed solution, and may in some cases override all of them.

A methodology for integrating divergent assessments of risk of expert and local or lay populations will identify the constraints underlying the separate assessments, and provide risk policymakers with a tool for systematic prioritization. The strengths and potential contributions of the two groups differ, and risk policymakers need to be sensitive to the differences when they seek to integrate these divergent views. In the infrastructural intervention mentioned above, for example, the two sets of constraints would overlap in terms of requirements that the resulting structure, e.g. a road or a bridge, satisfy conditions of functional adequacy which are common property (at least at a certain level of description). These will typically be resolved by the experts into a number of technical requirements that could not even be formulated by the lay agents. In addition to these constraints, desiderata of non-redundancy and cost minimization may also come into play. On the lay side, fundamental constraints on an acceptable infrastructural intervention may be suggested by the basic scheme of intrinsic values in the lay population, which may constrain where and when the intervention can take place, or what local natural and or human resources can be utilized for it.

Figure 2.1 visually represents integration processes that chart the constraints assumed to underlie expert and lay public risk assessments. These spider diagrams are visual displays of the degrees of simultaneous satisfaction of constraint sets. If the expert and lay assessment are generated by two sets of well-defined constraints whose degree of satisfaction can be measured in some way, then both the expert and the lay public assessments can be described by such diagrams: the distinct axes of the diagram represent dimensions of appraisal corresponding to distinct constraints; the closer to the edge the relevant vertex, the greater the degree of satisfaction of the associated condition. We want to define a superposition of the diagrams associated with the experts and the local or lay population in order to achieve a combined representation of optimal outcomes and, correlatively, risks. In the combined diagram, it may happen that only a subset of the lay constraints are used, and so a key question becomes how these are to be identified. We take up this problem below. In this simple example, both the expert and host populations operate with a four dimensional evaluation, and in the combined diagram the original four dimensions of the lay evaluation are redacted to two.

In our framework, then, we assume given a local lay population P and an expert population E. We think of P as endowed with a set of social desires or goals that the members of E are attempting to help P realize. In addition there is a set R of possible outcomes that represent the possible social situations involving P that can arise from the available interventions. There are two social preference orderings, $\prec_P$ and $\prec_E$ on R that represent the rankings that P and E assign to the outcomes in E. These preference orderings are in turn generated by two sets of constraints

$$\begin{array}{l} C_E = \{A_1, \ldots, A_n\} \\ C_P = \{B_1, \ldots, B_m\} \end{array} \tag{2.1}$$

associated with the expert and the lay populations. These are conditions that the respective populations believe must be satisfied by the outcomes of possible successful interventions. These properties are supposed to be independent and irreducible; i.e., they are not conjunctions of other constraints, and are satisfiable independently of one another.[1] The success of an outcome relative to one these constraints is represented by an axis of one of the spidergrams above. Our idea is to define a measure of success as a sort of expected utility. In an expected utility computation, the expected value of an action is represented as a weighted sum of the probabilities of the distinct outcomes of the action; the weights reflect the value assigned to the distinct outcomes. The constraints A_i and B_i are associated with weights u_i and v_j for each i and j such that $1 \leq i \leq n$ and $1 \leq j \leq m$, that represent roughly their degree of importance in the respective populations. For each intervention (outcome) o and constraint $C, p(C, o)$ is the probability that C is realized on the intervention o. The overall success of an intervention o from the standpoints of E and P may be represented by weighted sums of these probabilities:

$$\begin{array}{ll} (a) & s_E(o) = \sum_{i \leq n} u_i p(A_i, o) \\ (b) & s_P(o) = \sum_{j \leq m} v_j p\big(B_j, o\big) \end{array} \tag{2.2}$$

The numbers $s_E(o)$ and $s_P(o)$ represent scalar estimates of overall success against the background of the constraints provided by E and P. Sums of type (a) will be called *design evaluations* and sums of type (b) will be called *local evaluations*. There is an easy algorithm for recovering a spider diagram from such a sum. For the expert spidergram, for example, we have n dimensions. Inscribe a regular an n-gon in a unit circle. If C is the center and for any $k \leq n$, P_k the kth vertex, the unit segment CP_k is the kth axis. The maximal optimal diagram for the situation described by the expert sum is the n-gon generated by the a point Q_k on CP_k such

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[1] The rationale for these requirements has to do with the role of these conditions in an expected utility computation, where the target utilities pertain to independent irreducible outcomes; see below.

that $|CP_k| = w_k$ and the actual spidergram for the situation o described by the sum is generated by the points R_k on CP_k such that $|CP_k| = w_k p(E_k, o)$.

In a representation of this sort, the risk $r(C, o)$ associated with the constraint C is on the intervention o is given by

$$r(C, o) = w[1 - p(C, o)] \tag{2.3}$$

where w is the weight associated with the constraint C.

The social preference orderings for these two groups may be recovered from the scoring functions in the obvious way. The orderings can differ between E and P because the scoring functions may not agree, and the scores come apart precisely because the underlying sets of constraints can and typically will differ. The principal problem is how then these divergent sets of constraints are to be combined or superposed in order to generate a unified preference ranking for alternative possible outcomes or interventions.

The obvious suggestion would be to simply amalgamate the constraints and their associated weights to form an $n + m$ dimensional evaluation framework. The difficulty with this idea is that some of the local constraints may not be pertinent to the normative evaluation of possible outcomes: the idea is that we wish, for example, to avoid infringing deeply held convictions of justice or religious or cultural norms of the local situation, but we are not constrained to respect contingent judgments of taste, however broadly shared they may be. And so our problem may be viewed as one of devising what might be called a normative filter for the local constraints, a means of selecting from the totality of socially desirable properties of outcomes the normatively relevant ones. Such a filtration process requires judgments about the relative moral importance of different kinds of consequences (e.g., death, economic loss, ecological damage) and the kind of priority that will be placed on achieving fairness in the distribution of risks.

The constraints in the design-evaluations are assumed to reflect fixed norms of expert practice, which include their own prior normative judgments about the projected outcome and its means of realization. Thus the normative filtration requirement need not be applied *ex post facto* to the design-evaluation sum. Still, the problem arises that even the normatively relevant design constraints may conflict with local normative constraints. The question is then how to adjust the weights in the local sum in such a way as to achieve a reasonable combined evaluation. Our suggestion is that in the combined evaluation, the weights drop to zero for constraints that are not generated by the basic scheme of intrinsic values of the population in question. Call such constraints *locally normative for P*. But it seems natural to suggest that the weights assigned to the constraints that are generated in this way should be maximal in the combined evaluation. This reflects the idea that the most important normative constraints in the local situation should be given at least as much importance as any expert constraint in the composite evaluation. And so the required filter may be represented by a condensation function f that maps positive integers $\leq m$ into $\{0, 1\}$; for any $k \leq m$, $f(k) = 1$ if

B_k is a locally normative constraint for P; Otherwise $f(k) = 0$. The combined sum would then be given by

$$s_{E+p(o)} = \sum_{i \leq n} w_i p(A_i, o) + \sum_{i \leq m} f(i) p(B_i, o) \tag{2.4}$$

If we think of the weights in this sum as normalized social utilities, that sum represents a superposition of the expert expected utility computation and the local expected utility computation based on normatively relevant local utilities. The present proposal, then, is an implementation of the idea that an acceptable intervention in the life of P must respect the basic scheme of values of P.

2.3 Part II

2.3.1 Cases

Let us begin with the following premise: in assessing risk, experts use data, expert opinion, financial considerations, and professional judgments as well as tolerable or acceptable levels of risk. Experts note that there is no way to avoid all risk, and this is especially true when it comes to natural hazards, and even if there were the costs were prove to be too prohibitive (World Bank 2012). At the same time the risks lay persons are willing to accept, along with how they perceive and determine risk is driven by "…their "world views" as cognitive and emotional filters that influence how they perceive and act with respect to risky situations, and as a way of simplifying decision making." (World Bank 2012) In addition, individuals armed with the same data and having no disputes with the data often will arrive at different risk assessment due to assigning weights, values, and priorities based on their own lives and lived experiences. Finally, it is important to underscore that

> [b]ecause factors that influence how people process information about risks are embedded in fundamental beliefs, judgments about these risks can differ markedly within a country and even more across countries (World Bank 2012).

In general, in the process of conflict resolution between expert and lay preferences, the problem is that even when appraised of expert information there can be a systematic discrepancy between the judgments of experts and the lay agents about desirable outcomes and specifically about judgments of risk. The two overarching general problems are

- Analyzing and understanding how lay or personal social preferences are derived. These are determined based on personal experiences, the ability to actually solve a problem with minimal disruption to daily life, and within the context of the prevailing cultural, social, political, familial, gender, and religious belief systems (World Bank 2012).

- Determining expert preference ordering by understanding and analyzing the overall macro level goal and the required technical desiderata. Macro level goals are generated through analyses of costs, resource availability, resource utilization, economic, and environmental impact, as well as overall morbidity and mortality rates. These data then are used for delineating a hierarchical ordering of what to 'attack' with experts and local leaders as well as governmental and non-governmental organizations making the decisions. These decisions are based on an overall ability to address a problem, the acuteness of the problem, and the perceived ability to solve the problem.

In this section we turn to two examples relating to risk assessment conflicts between laypersons and experts. [2] The two examples involve natural hazards and health.[3] The cases discussed below illustrate the difficulty of amalgamating the experts' assessments of risk and the lay populations' assessments of risk in order to find an equilibrium for integrating the lay and expert assessments, and therefore increasing the probability of identifying and implementing a practical and solution or intervention.

It will be clear from these examples that the data in the model developed above can be configured in such a way as to support the qualitative conclusions that are suggested below. Moreover, while the model is a necessary first step in articulating the structure of evaluation in these conflicting contexts there is an essential additional step that is required. Specifically, these examples will illustrate that significantly more attention must be paid to the role that public policies and economic support to victims, particularly of natural hazards, play in negotiating which risk assessments 'win out'.

2.3.1.1 Flooding

Turning to natural hazards we find a clash over risk assessment and acceptable levels of risk between experts and laypersons. Severe flooding in the Red River

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[2] While there is no disputing that risk management and the conflicts between laypersons and experts within that arena are important and warrant continued analyses, we contend that before we can begin to tackle risk management we need a better understanding of how risk assessment conflicts arise and might be mitigated.

[3] Although the focus of this paper is driven by considerations of risk assessment and natural hazards, we have included a health example because we believe what is needed is a study of the competing risk assessments between laypersons and experts when natural hazards and health interact. This area of research seems to be a pressing need as we confront ever-increasing numbers of natural hazards and growing problems of climate change. The complexities of examining the interaction of natural hazards and health are beyond the scope of the paper, but we believe that offering a case each of natural hazards and health may provide a starting point for integrating the two. In addition, the complexities of how to resolve competing risk assessments when natural hazards and health interact require its own analysis.

Valley, one of the most flood prone areas in the US, keenly illustrates the clash between layperson and expert risk assessment.

Regular flooding of the Red River Valley is severe. Significant negative impacts accrue to houses, farms, infrastructure (e.g., roads, sewers, sanitation), and businesses that are in low-lying areas or flood plains. In addition to significant technical changes, experts recommend "[b]uildings located in at-risk areas where structural measures cannot accomplish the recommended flood protection levels or are not economically feasible should be publicly acquired and removed over the next three to five years." (RRBC 2011). In addition, the commission recommends:

> "A review of basic **floodplain regulations and programs** should be undertaken by appropriate agencies and stakeholders of local, state and federal standards, to include:
>
> 1. An evaluation of the appropriate **standards and regulations for development** throughout the basin, including the adequacy of the 100-year regulatory minimum standard (to include FIRMS) and the consideration of future standards to reduce losses;
> 2. An analysis of community and state compliance with the **flood insurance** program, to include an analysis of proposed mandatory flood insurance for structures protected by dikes, identification of impediments to, and potential tools and resources for, participation in FEMA's community Rating System, determination of the feasibility of insurance development, and a strategy to prompt a basin-wide reduction in flood insurance rates;
> 3. An analysis of the use of **variances by local governments**; the reasons for and consequences of using variances for individuals, communities, and state; and most effective way(s) to track and document the use of variances.

In short, in addition to the technical and structural changes and monitoring that must occur, experts want evaluations and changes to where and how people live and in the case of flood insurance how they allocate some of their income. These recommendations, on the face it, appear reasonable and many might say without much controversy. But turning back to with the understanding that laypersons, especially those most directly impacted by expert assessments, all too often may have assigned different priorities and assessments.

In this case of the Red River Valley, people who for generations have lived in the area want to remain there and live as they always have. The assessment of risk and what is important in order to address and mitigate the damage associated with flooding diverges when the experts are examining the 'big picture' including overall costs and individuals themselves are examining what it means for their lives and that of their families and communities. Educating people about the expert assessment of risks associated with flooding in the area is important but it should not be assumed that such educational endeavors would produce a convergence of expert and lay assessments. People living in the area are well aware of the damage and costs as well dangers associated with flooding, but those data points are afforded significantly more weight by the experts than by laypersons.

In the Red River Valley there has been some success in buying land and structures and incentivizing people to move, but there are far more people who have chosen to stay. Risks associated with regular, and often deadly, flooding are to these laypersons not so great as to change where, and perhaps how, they live. To the experts the consequences associated with the Red River Valley flooding are so severe that significant changes are required. It is a cost benefit computation on both sides with experiences and emotions on one side and expert critiques, evaluations, and predictions on the other side.

When it comes to natural hazards, many times experts note that moving people and businesses out of the affected areas is the best course of action, all things considered. They are able to provide data documenting that conditions and risks will not change, and in many instances will increase over time. In short, experts often argue that sooner and quicker movement out of the areas with the highest risk of certain natural hazards (e.g., flooding) is the most prudent action to take. Experts also recognize that expenses associated with moving people and businesses need to be covered and providing the requisite monetary incentives should produce the appropriate level of out migration from the impacted areas. And while it is true that such incentives and prodding by experts and policymakers will induce some people to relocate, in far too many other instances people will insist on remaining in place. For those who do not respond to the expert and policy driven incentives, it is the assessment of roots, lifestyle, choice, history, and in some cases disbelief of the data that keep people ‘in place’.

However, when natural hazards are considered, there is the social and political reality that the economic and social incentives for people to stay often erode the credibility and legitimacy of experts, at least in the minds of the locals. In the US, for example, no government entity is going to tolerate victims of natural hazards or ‘acts of god’ to remain without some compensation to restore what was lost. Victims, in short, are bailed out. The political and economic institutional structures that support such bailouts to victims of natural hazards also have the unintended consequence of giving greater emphasis and priority to the risk assessments of laypersons. This occurs because in spite of the judgments of experts that out migration is necessary; the political and economic systems allow people to remain in place and it is their desire to remain in place that has won the tug of war between lay and expert assessments of risk.

2.3.1.2 Health

In health care we turn to the case of the Gardasil vaccine for the human papilloma virus (HPV).

> “Approximately 79 million Americans are infected with human papillomavirus (HPV), and approximately 14 million people will become newly infected each year. Some HPV types can cause cervical, vaginal, and vulvar cancer among women, penile cancer among men, and anal and some oropharyngeal cancers among both men and women. Other HPV types can cause genital warts among both sexes. Each year in the United States an estimated

(continued)

27,000 new cancers attributable to HPV occur, 17,600 among females (of which 10,400 are cervical cancer) and 9300 among males (of which 7200 are oropharyngeal cancers).

> . . . HPV vaccines available. . .which protect against the types of HPV infection that cause most cervical cancers (HPV types 16 and 18). . . .Clinical trials and post-licensure monitoring data show that. . . vaccines are safe." (http://www.cdc.gov/vaccinesafety/vaccines/HPV/index.html; 2014).

Gardasil is about preventive health care; this vaccine prevents certain cancers in young people. Experts point to the fact that vaccinating young people with it will lower health care costs and reduce premature morbidity and mortality. It is a vaccine that will reduce the number of a certain category of cancers; and it is safe (http://www.cdc.gov/vaccinesafety/Vaccines/HPV/jama.html).

When Gardasil was still in the clinical trial phase, lay arguments against it were structured to not only ignore what the experts recommended but they were designed to reframe the debate. The lay arguments moved the focus from cancer prevention to promotion of early coitus, and all the moral, health, and social costs associated with that. Parents and guardians who consented to or instigated the administration of the vaccine to their daughters would be encouraging and even condoning early sexual activity. Having the Gardasil vaccine would make teens think they were invincible and they would make riskier and more dangerous choices than if they were not vaccinated. And finally, there was the appearance of the claim that any vaccine was dangerous and unhealthy. The lay norms of not encouraging early or young sexual activity gained traction in many communities, as did the invincibility risk and the overblown risk assessments associated with the vaccine itself. In short the lay arguments avoided focusing on the experts' assessment of prevention and centered on normative arguments about sex, sexuality, risk taking behaviors of the youth, and, of course, the fear of anything vaccine.

As these arguments from laypersons took hold, the experts were faced with significantly less of the population likely to be vaccinated than was desirable, given the data, and therefore a non-trivial percent of the population being unduly exposed to life threatening cancers. It appeared highly improbable that there could be a successful amalgamation of the lay assessments and the expert assessments. In light of that, experts realized that they had to change the context in which lay assessments of risk were being "calculated" while also embarking on a course of countering the lay arguments and assessments of risk with expert data. In other words, experts not only provided data, with significant, albeit imperfect, success; they also reframed the context in which lay risk evaluation was calculated and evaluated. That did this by framing the decision to have Gardasil administered to your daughter in terms of cancer prevention.

Gardasil was defined as a necessary tool for preventing a non-trivial amount of deadly cancer in young people. In other words, in order to achieve the desired goal of administering Gardasil to a large proportion of the female population under the age of 26, experts did not argue it was not about condoning or encouraging sexual activity, rather, they reframed the context to be one of preventing a deadly cancer in your daughter.

This case is an example of expert and lay assessments being so incommensurable that the rational strategic response requires a reframing of the context in which assessments are "calculated", evaluated, and rejected or accepted. The experts knew they would not win or persuade with data that showed no relationship between receiving the vaccine and initiating sexual activity; there was no way to dislodge the beliefs based on faulty or irrational data and beliefs. Instead of focusing on Gardasil as being a vaccine against HPV, the discussion was reframed as a cancer prevention strategy. The data and rational arguments for why one should ensure their child was vaccinated with Gardasil became one of preventing cancer and who would not want to do that? However, in spite of the vaccine's safety and the ability of the vaccine to prevent a subset of often deadly cancers there is no requirement that young people be given the vaccine.

2.3.1.3 Summary

The limited resources available require a method for prioritizing the risks faced by society and selecting the most appropriate mitigation strategies. Any approach to making decision about interventions or mitigation strategies that specifies criteria for prioritization will reflect specific value judgments of both the local and expert groups. For example, many argue that proper allocation of resources should be concerned with avoiding hazards with greatest expected impacts or greatest risk to the population's health before allocating resources for those determined to be less damaging. How greatest risk is operationalized frames the priorities and determines where resources are allocated. In other words, which hazards or health risks are prioritized depends on which losses are considered most significant. If loss of life is the primary criterion for impacts, then mitigating or preventing severe tornadoes, for example, would be a priority; while in the case of health care, managing highly contagious infectious diseases with no known cure would take precedence. If, on the other hand, the criterion is economic loss, then in the case of natural hazards the emphasis should be placed on, for example, flooding and earthquakes, while in health care the priority should be chronic conditions such as diabetes. Which criteria are primary turns upon both the identification of the local normative constraints and the weights assigned to them.

2.3.2 Characterizing Local Constraints

The cases considered above point up the need to address four questions in characterizing the local normative constraints:

1. How are the locally normative constraints identified?
2. In what ways, if any, are the locally normative constraints sensitive to empirical background information? To the extent that they are, should an additional filter be introduced to eliminate or modify constraints arising from faulty background information?
3. Can an acceptable intervention justifiably ignore contingent preferences that are not derived from fundamental local normative constraints or the basic scheme of intrinsic values of the local agents?
4. Are there circumstances in which an intervention can legitimately violate normatively relevant local constraints or values?

The local normative constraints express the basic layouts, generated by what following Lewis (1974) we have been calling a 'basic scheme of intrinsic values'. When will a constraint express such an attitude? Roughly, when the *status quo ante* is preferable to any outcome that infringes the constraint from the local social point of view. Thus, where P is the population in question, let $< P$ represent the social preference ordering of relevant possible outcomes, and let α represent the status quo ante, the outcome resulting from the null intervention. Then a local normative constraint is as a condition C such that

$$(N) \qquad \forall x \ (-C(x) \rightarrow x <_P \alpha) \tag{2.5}$$

where the quantifier ranges over possible outcomes. This says precisely that the status quo ante is preferable to any outcome that does not satisfy C, which in turn implies

$$\forall x \ (\alpha >_P x \rightarrow C(x)) \tag{2.6}$$

i.e., any outcome preferable to the status quo ante satisfies C.

A vexing question concerns cases in which an outcome that is preferable from the expert point of view to the current situation of P violates the local norms for P. The cases that naturally present themselves involve examples similar to the paradoxes of utilitarianism, cases in which an intervention that realizes a large-scale social good infringes a constraint that violates the lay norms. These may involve violations of individual rights or principles of fairness. Imagine that the society faces an existential threat if an intervention does not take place that infringes the property rights of certain individuals. An outcome involving this intervention in which these norms are violated might be held to be preferable to the existing situation. Of course in our own society, property rights are cancellable in the presence of appropriate compensation (as in eminent domain cases), which is another way of saying that in these situations there is no absolute right to property. If we imagine a social situation in which for whatever reason there is an absolute or un-cancellable such right, then the existing situation would be considered preferable to one in which it is violated from a normative social point of view. This scenario points to an open-ended class of cases in which questions 3 and 4 are to be answered affirmatively.[4]

Another family of such cases concerns question 2. The intervening agents may feel justified in ignoring a local social constraint if it is conditioned on empirical beliefs that the intervening agents judge to be simply *crazy*. In some cases it is tempting to incorporate such an attitude into the construction of the composite social preference ordering considered above. But it is necessary to be careful here. In many cases religious beliefs that ground local norms may be held by the exterior agents to be of precisely this kind. We cannot simply introduce a filtration scheme for the local norms that eliminate those based on information of less than a threshold epistemic probability from the external point of view; and it is not at all obvious what other demarcation could be provided. There is perhaps no significant distinction to be drawn between a case in which a bridge is not built in a certain location because the local agents believe that their wind-god will not permit it, and a case in which a vaccination regime is modified or discarded because of local religious objections to hypodermic injections. But what of a case in which the local agents cling tenaciously but without any good evidence to the wholly mistaken idea that there is a connection between vaccination and adult onset schizophrenia?

According to the criterion above, non-vaccination would constitute an admissible constraint if from the point of view of the local agents doing nothing at all is preferable to any outcome involving a vaccination regime. In this way the suggested criterion of admissibility is non-paternalistic: it allows any belief of sufficiently decisive importance to the local agents to ground an admissible constraint. We cannot say, for example, that such a norm must survive a sufficiently vigorous program of empirical reeducation without opening the door to the requirement that some the religiously grounded norms have to similarly stable. One way of motivating a distinction between the two sorts of cases is to somehow characterize the factual beliefs which are basic to the social identity of the local agents (which would include those constitutive of fundamental religious norms) from beliefs which, though highly stable, are ancillary to their social identity. This is not, however, a task we shall undertake here.

Finally, we wish to note the following methodological points deserve emphasis: Any strategy for integrating lay and expert assessments must include an evaluation of

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[4] However, a problem of circularity for the above criterion arises if the existing situation itself involves violations of fundamental norms. A situation in which fewer of these norms are violated should presumably be considered preferable to the existing state of affairs from a social point of view, but it is not so counted on (N). It must be assumed that the actual situation does not involve violations of fundamental norms. This seems a significant limitation on the application of the suggested criterion.

- The robustness of the validity and reliability of each set of assessments.
- The inclusion of known short and long term consequences as well as a factor for managing uncertainties or unknowns.
- A determination of the practicality and soundness of the decision for how resources are to be allocated in addressing or mitigating situations or conditions.

2.4 Conclusions

The formal model developed in the first part of this paper constitutes a broadly decision-theoretic framework for superposing the social preferences of expert and lay populations in a situation in which their collective judgments about an outcome conflict. What is crucial in the model are the criteria whereby one set of social choices override another, and in particular the role of the basic scheme of intrinsic values of the lay population in forming a combined evaluation. We have seen that there are situations in which both the local normative preferences and the expert preferences may take precedence; and within the set of expert preferences one can distinguish various normative dimensions.

The receiving community for a technical intervention does not have the detailed information relevant to evaluating the effectiveness, robustness and safety of a proposed design solution; equally, the intervening agents frequently lack access to the local normative structures that constrain proposed solutions. Finally, a third level of social decision floating above the two stressed in this paper is that of the policy determiners, who frequently lack full information from either the local or expert dimension of appraisal. It is at this level, in practical terms, that the superposition problem for the divergent social preferences more often than not gets resolved, and it is at that level that the tools developed in this paper are most appropriately applied.

At the same time that the model developed in this paper is a necessary step in better analyzing and understanding the tensions and divergences between lay and expert risk assessments, especially in terms of natural hazards, a take away message from the cases is that individual freedom and choice along with government's reluctance to strong arm laypersons who do not embrace the expert assessments and act accordingly play a very important role in how conflicts between expert assessments of risk and lay assessments of risk are negotiated. A next essential step in illuminating how lay and expert risk assessments are integrated is a better understanding the role that public policies play and whose 'side' they are in the ongoing struggle between laypersons' and experts' assessments of risk. The political realities are such that shifts in public policy that fully embraces experts' assessments and recommended courses of action are not likely to come anytime soon. Nonetheless, the expert risk assessments take a larger more macro level all things considered approach to natural hazards and therefore it could be argued are better for society as a whole. Given that, perhaps it would behoove experts to be more cognizant of the larger political and economic contexts and incentives as they themselves determine risk assessments and propose solutions.

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Chapter 3
Vulnerability to Natural Hazards: Philosophical Reflections on the Social and Cultural Dimensions of Natural Disaster Risk

Mark Coeckelbergh

Abstract Risk analysis and risk management are ways for humans to cope with natural disaster risk. This chapter connects discussions about risk with reflections on nature, technology, vulnerability, and modernity. In particular, it raises questions regarding the natural/human distinction and how human societies and cultures (should) cope with risk. How "natural" are hazards, given human interventions in and interpretations of events, and what are the limitations of "objective" modern approaches to risk? The chapter argues that coping with risk related to natural disasters should be sensitive to the social and cultural dimensions of risk. For this purpose it proposes the concept of "vulnerability transformations". It focuses on the experience and phenomenology of natural hazards in relation to existential vulnerability, and, taking a cross-cultural perspective, shows that apart from modern scientific thinking there are also other, less modern ways to cope with natural hazards.

3.1 Introduction

Natural hazards such as earthquakes, tsunamis, hurricanes, floods, droughts, and wildfires can have disastrous consequences for human lives and environments. Risk analysis and risk management are ways for humans to cope with natural disaster risk: they aim to better understand the potential impact of natural hazard events and to develop strategies to manage and reduce the risks related to these hazards. Engineers, economists, planners, and other scientists and technologists work together to assess risks and to develop plans and measures to mitigate the risk. This is done at local, national, and global levels and has ethical and political aspects. For instance, the United Nations Office for Disaster Risk Reduction

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(UNISDR) uses the concept of 'Disaster Risk Reduction' which aims to reduce the damage caused by natural hazards through an ethic of prevention: in order to reduce potential impact, choices have to be made concerning agriculture and land management, built environment, government, finance, and education. It also involves improving the preparedness of people and putting in place early warning systems.[1] In other words, the aim of this and similar programs is to reduce *vulnerability* to natural hazards by using scientific methods of risk assessment and risk management, which then informs policy and has consequences for society.

Philosophy of risk and philosophy of science and technology may contribute to discussions about these topics by revealing and critically discussing more or less hidden philosophical assumptions made by engineers, policy makers, and others involved. In this chapter, I am especially interested in issues that invite reflections on nature, technology, vulnerability, and modernity. I will show how discussions about natural hazards and management of natural disaster risk invite questions about the natural/human distinction, about how humans can and should cope with risk, about human vulnerability, and about modern culture. Furthermore, I hope that making these connections between risk management of natural hazards and wider social, cultural, and philosophical issues is not only interesting for philosophers but is also relevant to policy makers, engineers, and other stakeholders.

Let me start with two philosophical questions invited by every topic of risk management of natural hazards. First, what does it mean to say that hazards are "natural"? Are they "natural", given human interventions in natural processes and events? Second, to what extent is a scientific assessment and, based on this assessment, management of these risks possible and desirable? What are the limitations of "objective" and modern methods of dealing with risk? Are they necessarily the best and only way of coping with risk?

This paper raises and discusses these questions and then opens up the discussion to wider discussions about vulnerability and modernity. Using work in social geography, philosophy of risk and vulnerability, political philosophy, and anthropology (as reflected in UN reports and in the media), I argue that coping with risk related to natural hazards should be sensitive to the social and cultural dimensions of risk, to the ways in which social arrangements, risk experience, cultural meaning, and technology contribute to the construction of human vulnerability to natural disasters.

First I question the notion of "natural" disasters and argue that both the causes and effects are shaped by human interventions and social-geographical arrangements. Philosophy of technology, political philosophy, and other (sub)disciplines inside and outside philosophy can help to better understand and evaluate these natural-social entanglements. For example, we can study the social and cultural dimensions of risk in terms of "vulnerability transformations": a concept I coined to reflect my view that human vulnerability is not something 'objective' but is shaped by cultural and technological responses to risk (Coeckelbergh 2013). I will show

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[1] http://www.unisdr.org/who-we-are/what-is-drr

that we can study the unintended effects of technologies that were meant to reduce risk from natural hazards but which create new, technological risk, thereby transforming rather than diminishing human vulnerability. We can also use political-philosophical principles and methods (e.g. prioritarian or sufficitarian principles) to evaluate the creation and fair distribution of natural hazard risk.

Then I focus on the experience of natural hazard risk, which phenomenologically takes the shape of natural *disaster* risk, and how this experience is always mediated by cultural ways of giving meaning to, and coping with, natural hazards and disasters. Drawing on my analysis of existential vulnerability (Coeckelbergh 2013) and learning from anthropological approaches to risk, I then further reflect on the phenomenology of natural hazards in relation to existential vulnerability, and take a cultural and cross-cultural perspective. By locating the experience of risk within a broader cultural and cross-cultural perspective, I show that modern scientific-technological thinking and management does not exhaust the range of experiential and coping possibilities we have in response to natural hazards. Giving examples of modern risk metaphors, understanding risk in terms of tragedy, and traditional ways of coping with natural hazards, I argue that thinking about natural hazards—technological-scientific thinking and thinking by lay people—is already embedded in our language and culture(s) and that non-modern perspectives on natural disaster risk challenge us to become more sensitive to, and acknowledge, limits to what scientific-technological thinking and managerial control can do in response to natural hazards.

3.2 “Natural” Risk? The Social and Cultural Dimensions of Risk

Natural hazards like flooding, earthquakes, hurricanes are called ‘natural’ because they are seen as resulting from phenomena and forces of ‘nature’. But how “natural” are natural hazards? In this section I argue that use of the term “natural” is problematic since “natural” and “human” aspects of natural hazards are entangled in various ways: (1) humans causally contribute to “natural’ hazards, and the consequences of “natural” hazards crucially depend on how humans prepare and respond to them, (2) vulnerabilities to “natural” hazards are socially created, (3) the way we respond to natural hazards is often technological, and (4) risk related to “natural” hazards is also a political issue. Moreover, (5) I will also argue that use of the term “nature” as meaning “non-human nature” is also questionable; humans are also “natural” in several ways, and to sharply distinguish between on the one hand “human” technological risk and “natural risk is therefore highly problematic.

First, there is often a human causal contribution to the origin of “natural” hazards, for example, when hazards are related to flooding or climate change. Even if in most cases it is unclear how exactly and how much human activities might contribute to a hazard and have contributed to a disaster, the origin of the hazard and the disaster is at least “mixed” human/non-human. As Murphy and Gardoni (2011) have argued, the sources of risks associated with natural events involve a significant human causal contribution. For instance, “the construction and modification of built and natural environments can alter the probability of occurrence of natural events and the character and magnitude of the impact that such events have” (Murphy and Gardoni 2011). They give the example of earthquakes: its impact depends on the reliability of the built environment and on how the community responds, both of which in turn depend on “socio-economic conditions of the region directly and indirectly affected by the earthquake” and the availability of international aid (Murphy and Gardoni 2011). Thus, while we may not be the ‘direct’ source of such risks, humans are at least an ‘indirect’ source: our actions influence the character and extent of these risks. For example, we can reduce the impact of earthquakes by not building in seismically active areas and by improving societies’ resilience and ability to respond to disasters. Furthermore, how we construct and modify our environment (built and natural) can even influence the probability of occurrence. Think for instance about how urbanization and coastal development have contributed to vulnerability to flooding (Murphy and Gardoni 2011).

Thus, the consequences of events such as floods, earthquakes, hurricanes, etc. differ a lot according to how humans prepare for them and respond to them, which in turn may be related to social-economic difference. For example, in some areas (e.g. where rich people live) there may be better mitigation measures in place against flooding than in others (e.g. areas where poor people live). Think about New Orleans and what hurricane Katrina did to the city[2]: given known vulnerabilities and risk and lack of proper defences—settlement in vulnerable areas was not discouraged and the protective structures were known to have significant limits—it is plausible to say that humans are at least also causally responsible for what happened. Causes of the disaster are then “natural” and “human” at the same time. (It must also be noted that in general cities are themselves human constructs and examples of human technological control; therefore anything that happens in and to a city cannot possibly be “natural” if that means no involvement of humans.) There are physical forces and processes, of course, but what happens to humans and their environment, and how it happens, are shaped by human action. Instead of talking about vulnerability to natural disaster or “natural” vulnerability, therefore, we better talk about “physical-social vulnerability” or vulnerability to hazard in general.

Consider also the approach taken in social geography. Susan Cutter has studied ‘how and why places and people are vulnerable to environmental hazards’ (Cutter 1996). By ‘vulnerabilities’ Cutter means ‘potential for loss’ but she broadens the definition from individual to social loss, to ‘the susceptibility of social groups or

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[2] Hurricane Katrina, a 2005 cyclone which flooded 80 % of New Orleans and 90 % of Mississippi coastal towns, was one of the most deadly hurricanes in the history of the United States and in addition caused a lot of damage to properties.

society at large to potential losses (structural and non-structural) from hazard events and disasters'. It is 'the hazard potential filtered through the social fabric of society' (Cutter 1996), rather than simply the expected (physical and economic) consequences of a hazard. She has argued that vulnerabilities to hazards such as hurricanes are *socially* created. These are often ignored, partly because they are 'hard to measure and quantify' (Cutter 2006) and thus do not fit into standard scientific risk and hazard assessment methods, which rely on measurement and quantification. In this way, social inequalities remain hidden. Consider again hurricane Katrina and how its consequences (and therefore also the hazard) were very much entangled with socio-economic issues. For instance, in damaged areas there were relatively more African American, poor, and unemployed residents; they bore a disproportionately large part of the storm's impact (Logan 2006). Failures in the Katrina case are thus connected to wider social and political issues:

> The revelations of inadequate response to the hurricane's aftermath are not just about failures in emergency response (...). They are also about failures of the social support systems for America's impoverished (...). The former can be rectified quickly (months to years) through organizational restructuring or training; the latter requires much more time, resources, and the political will to redress social inequities and inequalities that have been sustained for more than a half century and show little signs of dissipating. (Cutter 2006)

Given this social dimension of vulnerability to natural disasters, Cutter proposes to talk in terms of "a confluence of natural and social vulnerabilities" (Cutter 2006), a phrase which better expresses the interaction between humans and their environment. Furthermore, it is also the case that different cultures and societies deal differently with natural disaster risk, as I will show below. Thus, both causes and effects are shaped by human interventions and socio-geographical arrangements, and how we deal with natural hazards depends on society and culture.

It must also be emphasized that human intervention with regard to natural hazards often takes the form of technological action. But technologies also *create* risks and hazards. We can learn from the philosophy of technology that technologies always have unintended effects. I have argued elsewhere that technologies that were meant to reduce natural risk often create new, technological risk, thereby transforming rather than diminishing human vulnerability (Coeckelbergh 2013). For example, nuclear energy production was meant to reduce the risk of being dependent on carbon-based energy sources. But at the same time this technology creates new, nuclear risk (radiation risk). And flood control systems are great ways to protect against flooding, but they also render people dependent on the technological system (rather than "nature") and this creates a (new) risk: something might go wrong with the technological system. Again the "natural" and the "human"--technological are entangled. This is so because with regard to natural hazards our environment is always already shaped by human technological intervention; any "natural" hazard, therefore, concerns the human as much as the natural. Human vulnerability depends on technology as much as it depends upon nature.

Moreover, next to philosophical reflection on "natural" hazards we can also learn from political philosophy. In response to the unequal and perhaps unfair distribution of risk, we can use political-philosophical principles and methods (for example prioritarian or sufficitarian principles of justice[3]) to evaluate the creation and fair distribution of natural disaster risk. If there is a “politics” of risk—including “natural” risk—then political philosophy can help to deal with this aspect. For instance, one could argue that distribution of risk should be fair or equal, or that people should have the opportunity to participate in decisions about risk. For example, one might consider implementing a kind of Rawlsian “difference principle” to risk distribution and to coping with risk, which may imply that inequalities in risk are justified as long as risks are minimized for the least advantaged members of society (prioritarian principle). One could also define a threshold level of risk (sufficitarian principle). Of course in both cases, one would need to discuss what adopting either of these principles means in practice. For instance, if a prioritarian approach is adopted, what political measures would need to be taken to ensure that the relative position of the least advantaged members of society in terms of vulnerability to natural hazards (for instance those most at risk of their area being flooded) is raised? And is it possible, in practice, to ensure a minimum level of protection against risk from natural hazards for all citizens, if this is what a sufficitarian principle may require? Would the distribution of risk and vulnerability to flooding be unacceptable according to *both* principles? What flood risk mitigation strategies are (in) compatible with these principles of justice? Do all citizens have a chance to participate in discussions about risk and vulnerability, or is this currently the privilege of a political and technocratic elite? Should decisions about risk to natural hazards be democratized? I do not wish endorse or defend this or that particular approach to justice or democracy here; my main purpose in making these suggestions about natural hazard risk, justice, and democracy is to stimulate further discussion in the area of what we could call *the political philosophy of risk* given the significance of social issues in relation to “natural” hazards, and to illustrate that political philosophy has the resources to help us think about this.

Finally, if natural hazards are conceived as resulting from what goes on in “nature” *as opposed to* the sphere of the “human” this is also problematic. The assumption is that there is a sharp division between on the one hand humans and on the other hand “non-human nature”. But humans are also “natural” beings (whatever else they might be according to philosophers), they are also part of “nature”. This has consequences for the discussion about “natural” hazards and risks. If one accepts that humans are also “natural”, then it is very problematic to distinguish between “human” technological risk and “natural” risk. Technological risk, as a human action, is then also “natural”, and “natural” risks then includes risks to which, as I argued in this section, humans have contributed and which have important social and political dimensions. As I suggested before, given the

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[3] With regard to evaluating the justice and fairness of a distribution moral and political philosophers discuss different approaches to justice. A prioritarian approach means that it is important to benefit those who are worse off, regardless of how high or low that position is in absolute terms. A sufficiatarian approach, by contrast, sets a minimum threshold for everyone, without addressing relative differences in position.

enormous scope of human action and intervention on this planet, it is even questionable—from a philosophical and a scientific point of view—if there is still room for the notion of a "non-human nature" at all when it comes to natural hazards. For example, "natural" hazards related to climate change are "human" in so far as humans contribute to climate change. And if natural hazards are always also social and political, making and assuming the human/nature distinction is no longer an adequate way of describing the phenomena and structures of so-called "natural" hazards. For instance, risk of flooding is as much dependent on the social-geographical and political-geographical structure of a city and a society (and technological and other preventive measures taken) as it is dependent on what goes on in "nature".

3.3 "Objective" Assessment of Risk? The Limitations of "Objective" Methods of Risk Assessment and the Phenomenology of Risk and Vulnerability

Let me now turn to my second question: Are modern risk management and "objective" scientific methods necessarily the best and only way to cope with natural disaster risk? I use the language of 'coping'[4] here rather than that of 'mitigation' or similar terms, since I want to emphasize that scientific-technological thinking is only *one* particular way of dealing with risk (I will show below that there are others) and I want to emphasize the involvement of *human* experience and culture in dealing with risk and vulnerability—an involvement which, if taken seriously, casts doubt on the scientific-technological definition of risk and vulnerability itself. Let me explain this.

When we discuss and cope with natural disaster risk and hazards, there is always human thinking, perception, experience, knowledge, and language involved. At first sight, this looks like a banal observation. But it has important questions for the epistemology of risk and hazard. It means that our knowledge of risks and hazards is always mediated by human thinking, language, and experience. There is no hazard-in-itself and no risk-in-itself. It is always risk and hazard as perceived, known, and talked about by humans. Therefore, what we call "objective" risk assessment and risk management methods merely represent *one* possible way of perceiving and coping with risk, and one which denies the subjective dimension of risk. As I will show in the next section, there are different options.

This argument should not be confused with the claim that risk is "subjective", *rather* than "objective"; instead my point is that risk is neither objective nor subjective, or that it is both. Usually risk is seen as either "objective" or as

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[4] My choice of the term 'coping' is influenced by the pragmatist and phenomenological traditions in philosophy; in particular Dewey's philosophy and Dreyfus's Heideggerian work on skilful coping.

"subjective"—the latter of which is then made "objective" by means of psychology of risk perception (e.g. Slovic 2000) which records, collects, and studies risk perceptions and attitudes in the service of risk management. But as I have argued previously, "risk is neither a feature of the world (an objective, external state of affairs) nor (. . .) a subjective construction by the mind, an internal matter, but is constituted in the subject-object relation" (Coeckelbergh 2013). Risk is about what may happen to us due to forces "out there", but at the same time this is always *experienced* risk. There is an experiencing, human subject, which always "touches" the object. We only have epistemic access to risk and hazard as a "phenomenon"; it cannot be accessed directly but always appears *to* humans, reveals itself *to* humans (to use the language of Heidegger). Again, there is no risk-in-itself; it is always mediated.

By conceptualizing risk in terms of existential vulnerability and "being-at-risk", I have therefore attempted to move beyond the objective-subjective and internal-external dualities that frame the current discussion. Being-at-risk means that risk and vulnerability emerge from what happens in the relation between subject and object. Science and risk management objectify vulnerability into an external "risk" that can be measured and managed. But risk is always *experienced* risk, and talking about it in terms of objective measures and states of affairs (and probabilities etc.) is only one way of looking at it and experiencing it, and a way which neglects personal and cultural risk experience. The techno-scientific language of risk management and hazard mitigation is itself only *one* way in which risk and hazard may appear to us, one way in which it is revealed to us (and one way we reveal it). At the same time, vulnerability is not only about "me" or "my body" but is always directed at an object; there is always some-thing that may happen to me. Being-at-risk is always directed at something, something which then may produce fear in me, for instance when I am afraid of a tsunami that might happen. Neither the object nor the subject can be crossed out. For example, it does not make sense to talk about flood risk without taking into consideration what it means for the vulnerability of humans understood as an *experienced* vulnerability.

In my book, I use the term "vulnerability" to emphasize this subjective-experiential aspect of risk. In response to "objective" approach to risk I try to redress the balance. If techno-scientific approaches to risk (such as risk assessment and risk management) "forget" the subject, it is time to bring it back to the stage. It is important to pay attention to the many ways we can and do experience risk and vulnerability, including risk related to the natural hazard. For instance, if people are vulnerable-to-floods then to discuss this experience and coping with floods only in terms of an external risk and hazard colonizes the discussion about risk and vulnerability in such a way that the personal and cultural experience of risk is marginalized, if not excluded. This denies the rich variety and broad range of experiences of risk and vulnerability in human culture and reduces the plurality of perspectives on risk and vulnerability to *one* particular perspective (whereby, as said, it is denied that there are other perspectives).

Again, this does not mean that risk is (only) subjective. Equally, it does not make sense to talk about, say, vulnerability to floods without considering how that vulnerability comes about. There is an object (for example one perceived as "nature", "the tsunami", "the flood", etc.). Yet from the moment I perceive it, think about it, or speak about it, it is already "colored" and shaped by my experience. There is no "objective", naked risk. This is my "personal" experience and at the same time "cultural" experience. The way we perceive and discuss risk and vulnerability is framed by the way our society and culture thinks about risk and copes with risk. (Below I will say more about culture.)

Applied to thinking about natural hazards, this approach could be called the phenomenology of natural hazards and existential risk, and research within this framework then focuses on the experience and cultural mediation of risk. It seeks to develop a phenomenology of natural hazards and existential risk, and opens up cultural and cross-cultural perspectives which show that our ways of perceiving and dealing with natural risk and hazards are not limited to modern scientific-technological thinking. Modern risk management is only one way of understanding and coping with natural risk and hazards; as I will show in the Sect. 3.4 there are different options. I will give examples of modern and non-modern ways of perceiving, understanding, and coping with natural hazards. Important for now is that my exploration of these different options is made possible by the recognition of the role of human subjectivity in the construction of hazards and risks, which leads to a rethinking of the epistemology of risk and opens up thinking about different ways of being-at-risk, being-vulnerable. This then enables us to reveal social and cultural differences when it comes to experiencing and coping with hazards and risk, differences which remain hidden when they are covered with the blanket of "objective" risk assessment and management. Let me show now that and how thinking about natural hazards is already embedded in our language and culture(s). I will pay particular attention to risk experience in the context of *modern* cultures as opposed to other ways of experiencing and coping with risk and vulnerability. While this angle cannot do justice to the full variety of and within what I will call "vulnerability cultures", it offers an example of what the proposed approach can do for thinking about natural hazard risk.

3.4 "Natural Hazards" and Vulnerability Cultures

To conceptualize the cultural mediation of risk perception and coping with risk, I propose the term "vulnerability cultures": there are various ways of perceiving, understanding, and coping with natural hazards. Let me give some examples of modern and less modern ways of understanding and coping with natural hazards and risk in order to better understand *that* there are different vulnerability cultures and to explore *different*, less modern vulnerability cultures. [Note that I say "modern and less modern" and not "Western" and "non-Western" since these terms are rather problematic in many ways; for instance today societies in the "non-West" (and indeed in the "West) are probably better understood as blends or hybrids of modern and non-modern culture, or even as new versions of modern culture incorporating some less modern aspects. This is also why I use the term "less" modern instead of "non-modern"—let alone "pre-modern" which has its own additional problems.]

A first example of how people experience and cope with natural hazards in culturally different ways is Dutch flood control. Flood control is a vital issue in the Netherlands since two thirds of its area is vulnerable to flooding and at the same time densely populated (Wikipedia 2014a). If the Dutch did not have flood control, a large part of the country would be flooded. In the history of the Netherlands, dikes, dams, and other means of protecting people against flooding (water from the North Sea and the rivers Rhine and Meuse) have therefore played an important role. In the twentieth century, the North Sea flood of 1953 was a major flood and disaster causing much damage and deaths. In response a huge storm surge barrier was created at the Oosterschelde (the so-called Delta Works) as well as other sea defenses. In addition, according to the dominant story (one may also say: "myth") the Dutch have always "taken" land from the sea in order to create more space for human activity. Culturally speaking, then, the Dutch dikes and other flood control systems thus emerge as technologies that are part of a (heroic?) fight against nature. "Nature" reclaims "its" land, but humans fight back.

Now this is not an "objective" history of natural hazards; it is at the same time a history of technology *and* a cultural history and a myth which interprets and gives meaning to the past, the present, and the future of coping with natural hazards (i.e. flooding) in the Netherlands. Furthermore, this interpretation of a Dutch natural hazard issue is not merely a "layer" that is put on top of the "objective", "hard" physical reality of flooding hazards; it is an interpretation that is made possible by flooding hazards which are *already* perceived, told, interpreted, and mythologized, by scientists and by lay people alike. There are no "naked" hazards here. There is not even a naked body and a dress, or the "facts" versus the "myth". We only have access to an already constructed, framed, tattooed body, co-shaped by humans, technologies, and "nature". It is fact and myth at the same time (or it is neither). Flood risk is not merely *embedded* in Dutch culture and interpreted in a culturally specific way; it *is* culture, it is part of Dutch culture and Dutch identity.

Another example is the cultural interpretation and construction of (people's response to) tsunamis in Japan, or better since in line with what I said previously: "Japanese Tsunami culture". Because of its location in the Pacific Ocean Japan has known many tsunamis in its history. Relatively recently, there was the Fukushima tsunami which led to a nuclear disaster. This has invited several cultural interpretations (see below). But before turning to this, it is worth noting that tsunamis are by no means a merely Japanese phenomenon. For example, in the eighteenth century the earthquake and tsunami of Lisbon in 1755 was also object of interpretations and public debates, in which philosophers and scientists participated. Was it due to divine punishment, or to natural causes? Are we living in the best of all possible worlds (Leibniz) or is there no benevolent deity who supervises us, as Voltaire suggested in *Candide*? Is it because we live too close together in cities, as Rousseau thought? (Given the phenomenon of megacities built in areas vulnerable to natural disaster he seems to have a point…) Or is it all due to natural causes, as Kant argued? Thus, also in "the West" and in a society and culture which we now would describe as "modern" natural hazard was not only a matter of "getting the facts right" but also a social, cultural, religious, and philosophical issue. It was not only about "natural facts", "natural causes", and "natural processes" but also about how we should live in cities, about the nature of the world and our relation to the divine. Different interpretations and constructions were admitted to the public discussion; none was excluded *a priori*. All views were attempts not only to assemble the facts and to "explain" but also to cope and to "make sense": to cope with and to make sense of natural hazard and risk, and to cope with and to make sense of human existence.

More generally, in the course of the history of "Western" civilization there have been many ways of understanding and coping with risks—natural and others, some of which seem to be rather different from our own. Ancient Greek tragedy plays, for instance, suggest that the Greeks were much more ready than we are to accept lack of full human control. Humans were portrayed as being in the hands of fate and it was suggested that they should not challenge the gods by fighting against it (*hubris*). This is a different, non-modern way of coping with risk, one that emphasizes acceptances rather than struggle against nature (see again Dutch flood control) and one that—like the debate in the eighteenth century—also involved talking about the divine, but then from a polytheistic point of view. Here a modern techno-scientific approach such as risk assessment and risk management is completely absent. Science, philosophy, religion, and theatre were not yet divorced; strict distinctions between these activities and ways of thinking are a later development—indeed a very modern phenomenon.

Another view (or rather cluster of views) which bears some similarity to the ancient Greek view, but has of course its own unique features, can be found in less modern currents and elements in Japanese culture that are related to natural religion (Shinto) and Buddhism. An attitude of acceptance seems to be also a *part* of the way Japanese people respond to natural hazard—at least *in so far as* their experience and culture is still shaped by Shinto and Buddhism. As a sensei of a Buddhist temple explains when asked why the Japanese reacted in a "stoic" way to the recent tsunami, people believe that 'things happen' and that the universe does not necessarily conform to our desires and believes.[5] Natural disasters then are not an offence against us or a punishment for our sins (as modern and Christian thinking has it) since it is not believed that humans are the centre of everything. The message is: we have to respect the forces of nature. These forces are as much "natural" as "divine", but divine in a non-Christian sense. The gods of nature are much more powerful than us, and they are not particularly concerned with us. Consider also the origin of the word *kamikaze*: it means "divine wind", typhoon (*kami* means god, deity; hence the god of the sea, the god of the wind) (Wikipedia 2014b). If and when these views play a role in understanding and coping with natural hazard such as tsunami hazard, one could say again that the hazard is not something that is isolated from the rest of

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[5] http://www.buddhistchannel.tv/index.php?id=44,10031,0,0,1,0#.VFS8EnkqWUk

human culture and experience; instead knowing and coping with natural hazard is part of Japanese culture, a culture which—like elsewhere, also in the West—is historically developed and includes stories, myths, and beliefs about humans and the divine.

Note that these traditional understandings of risk do not necessarily go against the findings of science. On the contrary, they often converge. This is especially clear in for example Japanese culture, which is often explicitly recognized as displaying a blend or hybrid of modern and non-modern elements (in the West these non-modern elements much less openly recognized and made explicit; there more work is needed to foreground them). For example, when someone speaking of Shinto in relation to the recent tsunami and nuclear meltdown in Japan refers to "a remarkable arrogance and disrespect for traditional understandings of the power and spiritual forces that reside in the land"[6] he does not mean, I presume, that science cannot help us to decide where to build the reactor or that science got it wrong; he means that Shinto understanding of 'forces that live within the land' would have identified dangerous cracks in the earth, which (I presume) are in principle also discoverable by science, but different decisions have been made which go against Shinto wisdom and (I add) against science. Perhaps we could say that Shinto offers a different epistemic route to the same insight, based on a different approach and culture. In principle, both approaches could have led to the same wise decision to build the reactor at a different spot. Thus, in principle it is possible for science and other types of knowledge and approaches to work together in order to cope with natural hazard—here earthquake and tsunami hazards.

Something similar can be said about the local indigenous knowledge about flood risk and other natural hazards and risks in other places in the world, which is revealed if we further study how various traditional and indigenous cultures cope with natural hazard. This is not at all an anti-scientific point. Today it is increasingly recognized that traditional knowledge can be valuable for this purpose. In a UNISDR (United Nations Office for Disaster Risk Reduction) report on early warning systems (United Nations 2006), it is acknowledged that when it comes to forecasting and dealing with drought hazards, traditional knowledge and values are important for early warning and a participatory approach is recommended:

> Traditional forecasting remains an important source of climate Traditional forecasting remains an important source of climate information in many rural communities. There is growing appreciation that traditional observations and outlook methods may have scientific validity and increased interest in harmonizing traditional and modern scientific methods of climate prediction. (United Nations 2006)

In the Asian-Pacific region, for instance, there is still relevant tradition and indigenous knowledge about hazards. As another UNISDR and ISDR (International Strategy for Disaster Reduction) report suggests, this knowledge can be used for disaster risk reduction. Examples include building earthquake safe houses in Kashmir, traditional irrigation systems for coping with drought in China, and traditional

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[6] http://blog.uvm.edu/aivakhiv/2011/03/16/religion-the-japanese-tragedy/

weather forecasting in Sri Lanka. Local information and story-telling (Shaw et al. 2008) can also be part of good practices in dealing with natural hazards. Singh reports on the UNISDR website about how indigenous people responded to a 2004 tidal wave:

> Among the 2004 tsunami survivors were the Moken of the Andaman Sea because they knew the tidal wave was coming. These nomads have a legend about the Laboon, the "wave that eats people". According to ancient lore, before the tsunami arrives, the sea recedes and the loud singing of cicadas is silenced as happened before the 2004 tidal wave. One member of the Moken noticed the silence and warned everyone. The community moved to higher ground long before the first wave struck and was saved. (Singh 2011)

Thus, here a legend in combination with traditional reading of signs and patterns worked perfectly well to protect people against disaster. This is also suggested by other examples given by Singh, this time from African local communities, which show again the value of indigenous knowledge for disaster risk reduction:

> Knowledge of storm routes and wind patterns enables people to design their disaster management long in advance by constructing types of shelter, wind break structures, walls, and homestead fences appropriately. Similarly, knowledge of local rain corridors enables them to prepare for storms. Knowing the color of clouds that may carry hailstones enables people to run for cover while an awareness that prolonged drought is followed by storm, thunder and lightning during the first few rains enables people to prepare for a disaster. A change in birds' cries or the onset of their mating period indicates a change of season. Floods can be predicted from the height of birds' nests near rivers while moth numbers can predict drought. The position of the sun and the cry of a specific bird on trees near rivers may predict the onset of the rainy season for farming. The presence of certain plant species indicates a low water table. (Singh 2011)

Traditional and indigenous knowledge thus helped and help people to cope with natural hazards; this is recognized by scientists and policy makers. Furthermore, 'coping' with natural hazards includes dealing with disasters when they occur. Again traditional ways of coping are important here. For instance, if a disaster happens and there is suffering and death, rituals help people to deal with it. Consider for example Japanese people who respond to natural disaster by means of praying for the spirits of those killed. But people in "the West" pray too and have their own mourning rituals.

Indeed, it must be doubted that in "the West" people always respond to disaster in a "modern", secular way. Arguably "the West" has never been entirely secular; there is a post-Christian culture and there is room for other, Christian and non-Christian religious understandings. It would be interesting to study non-modern elements in the ways people in "the West" cope with natural hazard and disaster. But whatever the precise nature of "Western" beliefs and practices, if the approach proposed in this chapter makes sense, it is clear that thinking about risk and vulnerability to natural disasters must also include thinking about society, culture, and religion. I have also suggested that perhaps we (academics, policy makers, scientists) can *learn* from less modern and less scientific ways of coping with natural hazards.

3.5 Conclusions

In this paper I questioned the term “natural” hazard and “objective” methods of risk assessment and risk management in coping with natural hazard. I have argued that so-called “natural” hazards always involve human action and human experience in various ways. I have also argued that risk is never entirely “objective” (and neither is it entirely “subjective”) and that vulnerability to natural hazards and the way we cope with them is always culturally mediated. Studying how other cultures respond to natural hazards can help us to cope with them. In particular, I conclude that reflections on vulnerability and studies of other cultures can help us to recognize limits to modern science and risk management: (1) they may help us to think beyond dualist objectivist (versus subjectivist) understandings of natural hazards and risks, thus going beyond a purely modern techno-scientific approach, and (2) they suggest that we acknowledge lack of full control (perhaps even integrate an attitude of acceptance) in our dealings with natural hazards and learn from traditional perspectives on, and ways of coping with, natural hazards and disasters. Finally, my interpretation of work published by the United Nations Office for Disaster Risk Reduction (and other work done in a similar context) suggests that rather than rejecting science or rejecting traditional methods, we better explore *combining* excellent science with traditional knowledge and indigenous good practices and rituals, for example when it comes to early warning systems and measures to prevent disaster (e.g. building houses). This advice is not only relevant for natural hazards in what some of us may perceive as “exotic” places and “developing” countries; it is worth considering in “Western” contexts as well. A cultural perspective on risk challenges us to think beyond the boundaries of standard scientific ways of thinking and dealing with risk and natural hazards. Ultimately, it also challenges us to question the values and attitudes of “Western” modernity. Thinking about natural hazards should not be restricted to thinking about “nature”; it should crucially involve thinking about our societies, our cultures, and ourselves.

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Chapter 4
Discount Rates and Infrastructure Safety: Implications of the New Economic Learning

Daniel A. Farber

Abstract Discounting is a tool used by economists to make tradeoffs over time. Discounting is relevant to disaster risks because they are generally low-probability and hence are not likely to occur immediately. The combination of low probability and the on-going nature of the risks make discounting especially salient for large-scale disasters. Because infrastructure can last for many decades in the future, the choice of discount rates can significantly affect assessments of the value of increased safety measures. An emerging consensus among economists calls for applying discount rates that are lower for risks farther in the future as compared with harms in the immediate future. The rationale is that long-term investments provide a hedge against uncertainty regarding future economic growth. Declining rates are also justified when portions of the population have low prospects for income growth compared with other societal groups. Inequality, particularly the future economic prospects of poorer individuals, matters in terms of discounting. Fixed discounting rates such as those now used by the U.S. government may undervalue disaster risks by using too high a discount rate. The implication is that society has been underinvesting in infrastructure resiliency.

4.1 Introduction

Because disasters are infrequent, we can expect them to be spread out over time. For instance, suppose that a levee has been built to withstand the "100-year flood," which means that there is a 1 % annual risk that the levee will fail. Assuming that failure is equally likely in all future years and that the levee will last 50 years, levee failure could well be decades in the future. This raises the question of how to account for the delay when determining whether the hazard level is acceptable. Although not everyone would agree that the delay is relevant to the acceptability of

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the hazard, there are substantial arguments for taking it into account, some ethical and some more pragmatic.[1]

Considerable controversy surrounds these arguments, but economists strongly support the use of discounting to determine the present value of future costs or benefits (Sunstein and Rowell 2007). The ethical debate over discounting is both fascinating and important, but it will be largely put to the side for purposes of this chapter. Given the widespread use of discounting by economists, engineers, and policy analysts, it is important to think through the proper way it should be done if it is to be done at all.

If discounting is used, the next issue is determining the discount rate. As it turns out, small changes in discount rates can have a dramatic effect on the present value of a future harm. Thus, this seemingly technical issue may have important consequences for policy makers who use cost-benefit analysis to set safety standards or to engineers engaging in performance-based design. Small changes in discount rates can sharply affect the present value of a future benefit or cost. For instance, the choice of discount rate can be decisive in formulating climate change policy (Weisbach and Sunstein 2009).

Economists' views about discount rates for long-term risks have been evolving. This chapter will discuss the relevance of this new economic learning to safety decisions regarding long-lived infrastructure. The upshot is that conventional discounting techniques probably undervalue the benefits of reducing disaster risks. Thus, greater safety precautions are warranted as a result of this reappraisal of discount rates.

The chapter will proceed as follows. Section 4.2 establishes the importance of discounting in infrastructure design. Section 4.3 then explains the new learning that justifies the use of declining rates over the long-term. Interestingly, the argument is based on two factors that might seem irrelevant to the assessment of long-term safety risks: uncertainty about the future trajectory of the economy as a whole and unequal income growth in different groups. The chapter closes in Sect. 4.4 with some general observations about the discounting issue.

Some readers may not be receptive to cost-benefit analysis as a method of decision-making or to discounting in particular. But the fundamental point does not depend on economic technicalities. Safety precautions serve the obvious purpose of preventing harm to individuals. What the economic analysis conveys, however, is that in the case of long-lived infrastructure, safety precautions can

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[1] One common argument for discounting is that individuals do not place as much importance on future harms as on present harms, and infrastructure planners and policy makers should defer to this preference. Another is that people in the future are likely to be wealthier due to economic growth, and we should be reluctant to transfer money from the people today to people in the future who will be relatively wealthy by comparison (Sunstein and Rowell 2007; for a contrasting view, see Carey 2014). One common argument for discounting is that spending money has an opportunity cost, on the assumption that money can be invested elsewhere and made to grow. I will argue has little relevance to selection of the discount rate.

also serve a more subtle function. These investments can help hedge against the risk of low economic growth or help groups left behind when the economy as a whole is growing. Whether or not the point is made in the language of cost-benefit analysis, this is a genuine social benefit that helps strengthen the case for investing in safer infrastructure.

4.2 The Significance of Discounting for Infrastructure Design

Disaster risks are relevant in two infrastructure-related contexts. First, infrastructure such as buildings, dams, or nuclear power plants may be at risk for catastrophic failure in the event of a natural disaster—a problem illustrated vividly by the recent nuclear meltdown at Fukushima in the aftermath of a tsunami. Second, infrastructures such as levees or seawalls are designed to cope specifically with disasters, but decisions must be made about how severe a risk to prepare for. In either case, the question is: how safe is safe? And, in either case, the likelihood that a long time will probably pass before the risk materializes is a relevant factor. This delay is relevant for economists doing a cost-benefit analysis of a project and for engineers using lifecycle analysis.

This section sets the stage for the theoretical discussion in Sect. 4.3 by showing the practical importance of the discount-rate issue in dealing with major infrastructure. Section 4.2.1 shows that the choice of discount rate can be critical over multidecade time spans. Section 4.2.2 is designed to establish a simple (and perhaps obvious) proposition: a great deal of critical infrastructure is likely to remain in use for many decades. Because of the long timescale, the choice of discount rates matters.

4.2.1 Discounting and Cost-Benefit Analysis

Discounting has dramatic effects over the span of very long periods. To take an extreme case, assume we are considering two proposals for nuclear waste disposal.[2] The first option is a storage facility that will last for 500 years but will leak and kill a billion people in the year 2515. On the other hand, no lives will be lost in construction of this repository. The second option, because of construction hazards inherent in its design, will kill one construction worker. The second design, however, will never leak or cause any later harm. Finally, assume a 5 % discount rate, which is consistent with government practice (OMB 2003). In this

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[2] For the sake of simplicity, also assume that the monetary costs of the two proposals are equal, and that construction of either repository would be completed in a single year.

Table 4.1 Effect of discount rate on present value of life saved in 20 years (given a "value of life" of $6 million)

Date	Discount rate (%)	Present value of life saved
1972–1992 (OMB 1972)	10	$894,000
Post-1992 (OMB 1992)	7	$1,560,000
Social cost of carbon (IWG 2013)	3	$3,324,000

hypothetical, if a policymaker uses cost-benefit analysis with discounted benefits, she will choose the first option because the one billion lives in the year 2500 have a lower present value than one life today (Parfit 1985). Implicitly, she is valuing a billion future lives as being worth less now than one current life.

Apart from nuclear waste disposal and climate change policy, few if any current-day decisions entail multi-century risks. Over shorter periods of time, the differences are less stark, but the fact remains that discounting significantly reduces the weight given to future harms in decision-making. Imagine a cost-benefit analyst analyzing a regulation dealing with carcinogens and faced with the following question: If society is willing to spend $6 million to save a life today, how much should it spend to save a life in 20 years? The government's answer to this question has changed over time, as shown in Table 4.1.

Note that cutting the discount rate from 7 to 3 % more than triples the present value of the life saved. That change could drastically increase the extent of precautions against the risk. Over longer periods of time, the differences are even more dramatic. For instance, over 40 years, changing the discount rate from 3 to 7 % cuts the present value almost 80 %, from $1,842,000 to $405,600. Over 80 years, the difference is $559,494 versus $26,934, an almost 20-fold difference.

The bottom line is that discounting makes a big difference in assessing costs and benefits over long periods of time and that difference is quite sensitive to changes in rates (Kane 2014; Weisbach and Sunstein 2009). Over multiple-decadal time scales, a minor shift in the discount rate can dramatically impact the analysis of whether additional safety measures are warranted. As we will see below, conventional analysis using fixed discount rates can substantially under-value risks materializing in future decades.

4.2.2 Infrastructure Lifespans and Disaster Risks

Several types of infrastructure present disaster risks if they fail and also have multi-decadal lifespans. Infrastructure safety involves sufficiently long time spans that growth uncertainty and declining discount rates are highly relevant.

Nuclear reactors are a prime example. The average age of U.S. commercial reactors is about 33 years. The oldest operating reactors are now 45 years old (American Energy Institute). Given the high upfront costs and relatively low operating costs of reactors, it makes sense to keep them running as long as possible.

As with other investments in infrastructure safety, improvements in reactor safety become more appealing with a lower discount rate.

Dams are another case in point:

> With the exception of seismic or weather events, age is a leading indicator of dam failure. In particular, the structural integrity and operational effectiveness of dams may deteriorate with age, and some older dams may not comply with dam standards established in the 1970s. Overall, more than 30 % of all dams in the NID are at least 50 years old, the designed lifespan of many dams, and more than 17,000 will cross this threshold over the next 10 years. (Lane 2008)

Because of the large number of dams constructed between 1950 and 1970, over 85 % of U.S. dams will be over 50 years old in 2020 (Lane 2008). Some major dams are even older. For instance, the Hoover Dam is now nearly 80 years old and does not appear to be near the end of its useful life.

The risk of dam failure is spread out over the lifetime of the project but apparently increases with age. Hence, dam failures decades after the construction of the dam are particularly significant in deciding whether to build a dam in the first place or how much to invest in a safer design.

Bridges provide a third example of very long-lasting infrastructure. For instance, the Minnesota Interstate highway bridge that collapsed and killed 13 people in 2008 was over 40 years old at the time. To save money, a design lacking redundancy had been used (Wald 2008). The average age of U.S. bridges is 42 years, but some are much older. As one engineering consultant said, “We’ve assessed infrastructures built in the early 1900s and sometimes the late 1800s. The design life for these structures was not 150 years—and some have already exceeded that. We’re in catch-up mode now” (McDonald 2014). By the same token, bridges built today are likely to be around for decades to come and some may be used for over a century—long enough for the use of a declining discount rate to make a huge difference in safety-related design decisions.

Commercial and residential buildings may also be long-lived. In New York City, for instance, as of 2010 the average large building in midtown was 57 years old; in midtown south it was 92, and downtown it was 63. The majority of the buildings in all three locations were over 50 years old. The Empire State Building is now 83 years old (Li 2010). Again, these are time spans long enough for the discount rate to matter considerably—and, of course, the average age during the present may underestimate the life expectancy of a new building today.

Water supply infrastructure may also be very long-lived, and failure could have drastic consequences if it accompanied some other form of disaster (Watson et al. 2007). By 2030, New York City’s water infrastructure will be over a century old (Li 2010). On the other side of the country, a 1925 tunnel supplying San Francisco’s water faces possible catastrophic collapse, with the potential for cutting off more than half of the Bay Area’s supply of drinking water (Lagos 2014).

Urban planning decisions can also be long-lived. Once a decision is made to allow residential housing in an area that may have high disaster risks, it may be very difficult to reverse that decision later. Indeed, even after a disaster occurs, it can be politically difficult to make land use changes to reduce future risk exposure, and what those changes that do take place may require expensive buyout programs (Farber et al. 2010). Thus, the decision to open an area to residential development can have a long temporal shadow.

The examples discussed so far involve infrastructure designed for other purposes but subject to potential catastrophic failure. Discounting is also important in designing infrastructure for disaster mitigation such as levees and seawalls, because such infrastructure is long-lived and decisions must be made about the degree of acceptable risk. Many levees are over 50 years old (Lilly et al. 2013). The Seattle seawall needed replacement after portions were a century old (Kevin 2013). In Massachusetts, 80 % of coastal structures have exceeded their 50-year design lives (Massachusetts DCR 2009).

The point is simple: a great deal of infrastructure is built to last 15 years or more, and in fact much of that infrastructure is likely to be used even after its design life has passed. Because of the long service life of infrastructure, optimal decision-making should be based on life cycle cost analysis (ASCE 2014). The age of current infrastructure suggests that the life span for infrastructure that engineers consider in their designs should be greater (or further in the future) than the time frame used to date. Given the age of current infrastructure, the probability of failure for infrastructure toward the end of their life is likely bigger than is currently recognized, due both to the effects of aging and to potential for more extreme weather events stemming from climate change. The length of the life of infrastructure makes even more important the selection of the discount rate, raising the question whether the rate should remain the same over the entire life of the infrastructure or not.

In designing infrastructure, therefore, we need to be cognizant of disaster risks that might materialize years in the future. Responsible infrastructure planning must account for potential disasters in future decades. The key question is how to do so. The following section addresses that issue.

4.3 Discount Rates for Long Term Disaster Risks

This section explains the economic theory in favor of using different discount rates over different time periods, so that harms 80 years in the future would be discounted at a lower annual rate than harms 20 years in the future. Section 4.3.1 presents the basic argument why discount rates should be lower for risks further in the future if we are uncertain about future economic growth or if growth will be distributed unequally among the relevant population. Section 4.3.2 shows that these are not merely theoretical concerns—there is every reason to expect these conditions to occur in practice. Section 4.3.3 discusses a technical wrinkle, that of correlation between disaster risks and economic growth. The key issue is whether we expect the probability of infrastructure failure or the extent of the consequences to be related to the future rate of growth of society as a whole or of affected subgroups. In practice, however, it is unclear whether this complication is significant. Regardless of the relationship between disaster risks and economic growth, it is clear that the choice of discount rate matters to long-term disasters, and that growing economic consensus suggests that engineers and policymakers should use a declining discount rate to estimate future harms.

4.3.1 *The Basis for Declining Rates*

We need to begin by seeing how economic growth is related to the discount rate. Consider an individual who expects future income to rise at a constant future rate. In considering whether to move income between time periods by borrowing or spending, this individual must consider the effects on utility of shifting wealth across time. For example, suppose the question is whether to invest money and receive a return at a future time t. Sacrificing current consumption in exchange for future income can affect the individual's utility in two ways (or three if we include opportunity cost). First, the individual might be impatient and simply prefer consumption today over consumption tomorrow. This might or might not be rational, but many people do seem to prefer immediate rewards to delayed ones. Second, an extra dollar has less value to a wealthier individual—it might be quite meaningful for a homeless person but completely insignificant to Bill Gates. Thus, if the individual expects to be wealthier in the future, an extra dollar of income may have less utility then, as opposed to today.

The Ramsey formula provides a useful way of teasing out the factors that go into the discount rate. The formula shows that the individual in this hypothetical would apply a constant discount rate $r = \rho + \theta g$, where g is the growth rate, ρ is an impatience factor, and θ reflects the declining marginal utility of an additional unit of consumption (For the derivation, see Gollier 2013).[3]

Much of the ethical debate around discounting concerns ρ, which measures the desire to experience higher utility levels earlier rather than later (Arrow et al. 2012; Revesz and Sahabian 2011). This factor is especially controversial when multiple generations are involved, since it implicitly treats benefits to future generations as intrinsically less valuable than benefits to the current generation. The next factor, θ, corresponds to individual risk aversion and also to the individual's preference for smoothing consumption over time (Arrow et al. 2012). This leaves us with g, the future growth rate. Over the past century, g has averaged around 2 %. A plausible estimate of ρ is 1 %, and a reasonable value for θ is 2. This adds up to a discount rate of roughly 4 % for safe investments.[4] It is worth observing that, despite the conflict over ρ (the impatience factor) it is actually only a fraction of the estimated discount rate, with the remainder relating to future economic growth.

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[3] Note that the assumption is continued long-term growth at a constant rate, which may not be realistic in a world of limited resources and environmental sustainability (Cooke 2012).

[4] In this context, "safe" means either that the return is certain or that any risks are completely diversifiable.

Note that the Ramsey formula discounts consumption based on utility differences, not based on investment returns. So in principle the two concepts are quite distinct. Market rates may provide a reality check on the parameters for the Ramsey equation (Arrow et al. 2012). But the relationship between Ramsey discount rates and investment returns is an empirical question, and in fact the evidence shows considerable disparities (Gollier 2013).

So far, we have assumed that future growth rate is known with certainty. Uncertainty about the future growth rate makes a big difference to discount rates, a point that traces back at least two decades to early papers by Weitzman (1998, 2001). The Ramsey formula assumes that future growth is known and incorporates risk aversion as another factor. When the growth rate becomes uncertain, we cannot simply substitute the expected growth rate for g. Because of risk aversion, we must also consider the risk that g may be higher or lower than expected. As it turns out, this requires significant revision in the Ramsey formula.[5] Uncertainty about income growth makes safe investments more attractive over increasing time periods, which justifies lowering the discount rate.

The reason is that the investing in a non-risky asset provides a kind of insurance against the risk of low growth (Farber 2015). Much like an individual investor moving into T-bills, despite the lower return, as insurance against stock market declines, investing in an asset with certain returns provides insurance against the possibility that over the long-run, economic growth will be weaker than expected. As a result, we are more willing to make the investment than it would be if uncertainty about the growth rate were ignored. In other words, the present value of the investment is higher. It increases for longer periods of time, because the effects of different growth rates pyramid over time and the insurance function increases accordingly.

There is an emerging consensus among leading economists that the discount rate for events in the far or even medium-term future are lower than the discount rates for more immediate events (Arrow et al. 2012). Over time, the discount rate starts to converge with the discount rate we would expect under the lowest possible growth scenario (Gollier 2013). As Weitzman has said, “in a world where we are fundamentally unsure about how distant future growth prospects could evolve, there are potentially strong forces that might make us consider using very low discount rates for discounting distant-future events,” due to the “fear-power of being so very unsure where the world is headed in the long run” (Weitzman 2012a).

Depending on how uncertainty is modeled, the discount rate could drop by as much as 1 % in two or three decades, 2 % in 50 years, and 3 % in a century or so (Arrow et al. 2012; Guo et al. 2006). Risky empirical evidence regarding the pricing of 100-year leases in England and Singapore suggests a very low discount rate in

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[5] In the limited legal literature discussing the topic, there is a tendency to phrase the issue as involving uncertainty about interest rates. But the issue is not volatility in financial markets as such. Rather, it is uncertainty about economic fundamentals.

the 1 % range for payments a century or more in the future (Giglio et al 2013), consistent with the predictions of the analysis above.

This argument shows that we should lower the discount rate if there are multiple scenarios in which society as a whole will have different levels of wealth. Suppose instead that the good and bad scenarios relate to different segments of the population or different countries, which experience very different growth rates over time.[6] We are still averaging between the two income trajectories, although now the trajectories apply to different population segments rather than different states of the world. Essentially, it makes sense for society to offer "insurance" against being left behind by economic growth. Investments that pay off equally for the rich and the poor thus provide a hedge against future (relative) poverty. The conclusion is that an investment with a certain payoff (or one with a diversifiable or insurable risk) becomes more attractive to a social planner than the same investment would be in a world where total growth is the same for both groups. The reason is that, as economic growth compounds, the group with the high growth rate ceases to care about the marginal return on the investment, whereas it remains more relevant to the low-growth group. Thus, the proper discount rate declines toward the lower discount rate of the low-growth group.

Declining rates matter for infrastructure simply because infrastructure can be so durable so that infrastructure failure in future decades is significant. But this might be only a theoretical quibble, if we have good grounds to expect a fixed level of growth and that growth will be equally distributed across society. As we will see in Sect. 3.2, however, it is too optimistic to assume that those conditions will hold.

4.3.2 *The Practical Relevance of Inequality and Uncertain Growth*

To determine whether the argument for declining discount rates is realistically grounded, we need to consider the predictability of future growth rates and the extent to which we can expect equal income growth across different populations.

At the international level, perhaps the most striking economic fact is the vast disparity in current wealth, reflecting disparities in past growth rates over long periods. Differences in current wealth levels are stark. In 2000, average income in the United States was $34,000, as compared with $2500 in India and $1000 in Nigeria (Acemoglu 2009). As of 2008, using a slightly different measure, per capita income in the U.S. was $47,930, compared with $520 in Bangladesh (Revesz and Sahabian 2011).

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[6] Of course, if the government could completely redistribute wealth in each time period, the disparity in income growth would not exist. But to raise this possibility is also to show its irrelevance.

Growth rates also vary sharply between countries.[7] From 1969 to 2009, the annualized growth rate was 1.7 % in North America, 7.4 % in China, and −0.1 % in Sub-Saharan Africa (Gollier 2013). There was slow convergence within OECD countries from 1960 to 2000 (Acemoglu 2009). There was also convergence in economies globally from 1969 to 2009, mostly due to high growth in China and India (Gollier 2013). In contrast, during the nineteenth and early twentieth centuries, there were sharp divergences in growth rates (Acemoglu 2009).

The high variability in growth rates between countries and over time within countries suggests that it would be a mistake to be confident about future growth rates. To take the most striking example, no one seems to have anticipated the explosive growth of the Chinese economic in the post-1990 period. A key factor in growth relates to productivity increases due to technological change. We cannot fully predict future technological change—doing so would be equivalent to predicting future scientific progress, which inherently involves the unexpected.

Growth inequality is as important for discount rates as the trajectory of total social income. In an important recent book, Thomas Piketty argues that there is a long-term trend toward greater inequality between labor income and capital income. On the basis of a carefully compiled database, he concludes that inequality increases during periods of low growth, which he expects to continue (Picketty 2013). In any event, a rising tide does not necessarily lift all boats, as the saying would have it. During the industrial revolution, the British economy grew quickly but wages were flat or falling (Acemoglu 2009). For the past three decades, while top incomes have grown rapidly, middle-class incomes in the United States have changed only slightly, as has the income of a typical full-time male worker (Stiglitz 2013). In the meantime, male high-school graduates have experienced a substantial decrease in real income (Stiglitz 2013). Thus, not only is income unequal within these societies, but so is income growth.

Recent evidence indicates that overall, relative inequality within developing countries was rising globally until recent years but has been decreasing until recently,[8] while inequality across countries has been rising. On average, the share of income going to the poor does not change on average with growth. However, within-country inequality in East Asia has risen steadily, indicating that some portions of the population are seeing faster income growth than others (Ravalion 2014). In China, the income ratio between rural and urban incomes nearly doubled between 1982 and 2004 (Shi and Chuliang 2010). In Indonesia, real consumption increased by 4 % annually from 2003 to 2010, but this average conceals huge disparities: a 1.3 % rate for the poorest 40 % but almost a 6 % rate for the richest 20 % (Economist 2014a).

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[7] In addition, growth rates have been much more volatile in developing countries than in developed ones, requiring a lower discount rate to hedge against the increased level of risk (Gollier 2013).

[8] Recent evidence suggests that developing countries are no longer catching up with developed ones (Economist 2014b).

In sum, we cannot predict with confidence the future growth trajectory of a particular economy, given that growth rates vary so much across time and across countries. There is also strong reason to believe that income growth will be distributed unequally over extended periods of time. Consequently, the theoretical argument for use of declining rates seems to have ample empirical foundation.

4.3.3 Discount Rate Adjustments When Safety Benefits Correlate with Wealth

The analysis so far has focused on discounting for risks that are known with certainty (or that can be covered by insurance or diversified away). In general, uncertainty about whether a safety feature will be effective should not affect the discount rate, although it obviously affects the safety value of the feature. But if the potential harm is correlated with the economy's growth rate, the issues become more complicated (Traeger 2013; Weitzman 2012b).

A simple example can illustrate the situation. As a baseline, consider a scenario involving a fixed level of return. Assume that an investment at Time 0 that will pay off with certainty at Time 1 with one unit of wealth. There are two equally probable futures: a high growth future where people will be four times as rich as they are in Time 0 and a no growth future where wealth is unchanged. Here, the investment actually provides a dual benefit: it has an expected return of one unit of wealth regardless of the state of the world, and it provides a hedge against the no-growth scenario. Thus, as discussed in Sect. 4.3.1, the discount rate should be lower than it would be in a world where future growth was known with certainty.

Now, consider uncertainty about the payoff of the project rather than just about the future trajectory of the economy as a whole. If the project risk is unrelated to overall future economic growth, then it can be diversified away. But suppose it actually is correlated. To make the analysis simple, suppose that the project is expected to produce almost no return in the high-growth future but return a payoff of almost two units of wealth in the zero-growth future (for example, it could be a safety precaution against a risk that mostly impacts the poor). The expected return on the investment has remained the same as in the earlier example (one unit of wealth), but the hedging function of the investment is much stronger since it pays off so well in the zero-growth future. Thus, by the same reasoning as before, the discount rate is even lower.

The fly in the ointment comes if an investment has the opposite characteristic: it pays almost nothing in the zero-growth future and almost two units in the high-growth future (this could be a levee in an area with low population, which we expect will grow rapidly if more people become affluent enough to live there.) Now, all of the return has been concentrated in a future where people will be wealthier and obtain much less marginal utility from a small increase in wealth. So, reversing the reasoning before, we can conclude that the net present value is even lower than it would be for a risk free investment in a world without economic uncertainty. Hence, instead of lowering the discount rate to account for uncertainty, we have to increase it. Investments that only pay off when people are going to be much richer anyway simply are less attractive.

The same argument also works in terms of inequality. Projects that deliver benefits concentrated on populations expecting low future growth should get higher present values and correspondingly lower discount rates, but if the benefits are concentrated on populations expecting high growth the discount rate should be increased instead.

The problem with making these adjustments is that it is often unclear how the benefits of safety correlate with future income levels. Consider the issue of climate change. If climate change is a larger problem when economic growth has been high (producing more carbon), limiting carbon may be a bad way to hedge against the risk of low growth (Gollier 2013). On the other hand, if the impacts of climate change are most severe for less affluent populations or if other severe catastrophes have already crippled the economy, then it becomes an even better form of insurance than we might otherwise think (Weitzman 2012b). Similarly, it is unclear what degree of income growth correlation we should assume for other safety measures.[9]

Suppose that we are considering a safety risk that involves only property loss. Property values will probably be higher in a high growth future, but it is also more likely that people will be able to afford other ways of safeguarding their property—for instance, better monitoring and disaster response, a better-equipped fire department, and so forth. Correspondingly, property values will be less in monetary terms in a low-growth scenario, but infrastructure failures due to poor maintenance, training, or supervision probably become more likely since resources are likely to be constrained. It is hard to know how these balance out. When the issue is loss of life, there is another complication: do we assign a higher monetary value to lives saved in a wealthier world or in wealthier parts of the population? The argument for doing so is that wealthier people are willing to pay more to avoid risks, but many people feel serious ethical qualms about valuing the lives of the wealthy as more valuable.

Given that we are not sure about the direction of correlation (if there is one), it makes sense to ask whether this uncertainty itself requires a modification in the discount rate, just like uncertainty about future rates of economic growth. Fortunately, however, the mere existence of uncertainty about the correlation does not

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[9] It is worth noting that disasters often disproportionately strike disadvantaged groups. For instance, in the case of Hurricane Katrina, among displaced blacks in Orleans parish, over a third were estimated to be poor. The poor were disproportionately able to evacuate because they lacked access to automobiles. In addition, “over 30 % of the most impacted population had incomes below one-and-one-half times the poverty line and over 40 % had income below twice the poverty line” (Farber et al. 2010). Thus, it may well be true that safety measures benefit the poor more than the rich.

require adjusting discount rates, in the absence of actual knowledge about the direction and extent of the correlation.

We can see this with a simple example. Imagine that we are making an investment but are not sure of how it correlates with future growth. In fact, we are completely uncertain about this. Specifically, suppose an investment is, with equal probability, positively or negatively correlated with growth. Either way, the correlation will be stark: If it is positively correlated, it will pay off one unit in the high growth scenario and nothing in the low growth scenario. The reverse is true if it is negatively correlated. Clearly, there are two possibilities because either growth will be high or low, with the following consequences:

- Suppose we are in the high-growth future. If the investment turns out to be positively correlated with growth it will pay off, but not if it turns out to be negatively correlated. Since these are equally likely, there is a 50 % probability that the investment will pay off in the high growth future, and an equal probability of no investment return.
- Using the same reasoning, we find that there is a 50 % probability that the investment will pay off in the low-growth future, depending on whether the investment turns out to be positively or negatively correlated.

Since the probability of the investment paying off is the same (50 %) regardless of whether economic growth is high or low, we see that the investment decision is growth-neutral. Our uncertainty about the correlation between project benefits and economic growth does not provide a basis for adjusting the discount rate from what it would be with zero correlation.

In particular disaster settings, we may have some basis for concluding that the expected amount of harm will be greater if future growth is high—or equivalently, if the injured individuals are especially affluent. Or we might be able to conclude the contrary. But in many cases it seems to be very difficult to make such forecasts. In default of specific information, we may be justified in treating the correlation as zero for purposes of determining future discount rates.

4.4 Conclusions

Over the multi-decade lifespans of major infrastructure, small changes in the discount rate translate into significant differences in the present value of possible disasters. Thus, the use of declining discount rates to account for uncertainty about future economic growth can have more than trivial consequences. Even in the United States, this adjustment is not insignificant, but it could be even more important for infrastructure in countries that have had highly volatile past growth rates.

Inequality in growth prospects can also become a significant factor, depending on local circumstances. Disaster risks may fall most heavily on the poorest segments of the population, which may have experienced little economic growth over time. As recent U.S. experience shows, inequality can also result in slow growth for the middle class. The wealthy, on the other hand, who presently seem to have high prospects for growth, are in the best positions to protect themselves from disaster losses either through physical precautions or loss-spreading through insurance. Certain types of infrastructure such as dams may have a tendency to be built in remote areas for geographic reasons, where prospects for growth may be lesser for at-risk populations. Thus, inequality could provide an additional justification for using lower discount rates for possible harms further in the future.

The shift to declining discount rates may seem like a technical detail. In a sense, of course, that is correct. But the practical consequence is to reduce myopia in risk management, increasing the present value of safety precautions. Thus, understanding how discounting relates to income growth patterns provides a supporting argument for more robust infrastructure.

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Part II
Future Challenges: Impact of Climate Change

Chapter 5
Setting the Stage for Risk Management: Severe Weather Under a Changing Climate

Donald J. Wuebbles

Abstract The most recent evaluations of the state of changes occurring in the Earth's climate through the 2013 Assessment Report 5 (AR5) of the Intergovernmental Panel on Climate Change and through the 2014 U.S. National Climate Assessment clearly indicates that climate change is happening now, it is changing rapidly, and that the primary cause is human activities. These assessments draw upon the latest scientific understanding of climate and climate change, synthesizing recent advances in the understanding of the science of climate change, and providing a succinct overview of the past and projected effects of climate change on the United States and the world. Findings include new analyses of the observed trends and projected future climate changes. Along with increasing temperatures over most of our planet, the pattern of precipitation change in general is one of increases at higher northern latitudes and drying in the tropics and subtropics over land. One of the major findings is that there has been an increase in some key types of extreme weather events, especially in heat waves and large precipitation events, in the U.S. (and throughout the world) over the last 50 years. There has been an increase in the number of historically top 1 % of heavy precipitation events across all regions of the U.S.—this is not surprising, as the atmosphere warms it holds more moisture. The analyses also indicate the trend towards large precipitation events is likely to continue to increase throughout this century. The drying of the subtropics and wetter conditions at more northern latitudes means that both droughts and floods are likely to be increasing issues in various parts of the world. Scientific analyses indicate a strong link between changing trends in severe weather events and the changing climate. In addition, there are many concerns about potential impacts of the changing climate, e.g., the effects of sea level rise on coastal areas. The aim here is to summarize the findings from the new assessments, plus provide a discussion of the current understanding of severe weather in relation to the science of climate change, with a special emphasis on the issues and remaining uncertainties affecting our future.

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5.1 Introduction

The science is clear that the Earth's climate, including that of the United States (U.S.), is changing, changing much more rapidly than generally occurs naturally, and it is happening primarily because of human activities (e.g., IPCC 2013; Melillo et al. 2014; UKRS-NAS 2014). Many analyses have concluded that climate change, often referred to as global warming in the media, is one of the most important issues facing humanity. While often debated in the media and on blogs, there is essentially no debate in the peer-reviewed scientific literature about the large changes occurring in the Earth's climate and the fact that these changes are occurring as a response to human activities, especially the burning of fossil fuels. Natural factors have always affected our climate in the past and continue to do so today; but now human activities are the dominant influence in many of the observed changes occurring in our current climate.

Along with the overall changes in climate, there is strong evidence of an increasing trend over recent decades in some types of extreme weather events, including their frequency, intensity, and duration, with resulting impacts on our society. It is becoming clearer that the changing trends in severe weather are already affecting us greatly. The U.S. has sustained 144 weather/climate disasters since 1980 where damages/costs reached or exceeded $1 billion per event (including CPI adjustment to 2013), with an overall increasing trend (http://www.ncdc.noaa.gov/billions/; also Smith and Katz 2013). The total cost of these 144 events over the 34 years exceeds $1 trillion. In the years 2011 and 2012, there were more such weather events than previously experienced in any given year, with 14 events in 2011 and 11 in 2012, with costs greater than $60 billion in 2011 and greater than $110 Billion during 2012. The events in these analyses include major heat waves, severe storms, tornadoes, droughts, floods, hurricanes, and wildfires. A portion of these increased costs could be attributed to the increase in population and infrastructure near coastal regions. However, even if hurricanes and their large, mostly coastal, impacts were excluded, there still would be an overall increase in the number of billion dollar events over the last 30 plus years. Similar analyses by Munich Re and other organizations show that there are similar increases in the impacts from severe weather events worldwide. In summary, there is a clear trend in the impacts of severe weather events on human society.

The harsh reality is that the present amount of climate change is already dangerous and will become far more dangerous in the coming decades. The more intense extreme events associated with a changing climate pose a serious risk to global agricultural production, energy use, human health and property, as well as the transportation, retail, service, and insurance industries that support and sustain economic growth. The purpose of this study is to summarize the findings from the new assessments, to examine the changes occurring in the climate, to discuss the current understanding of severe weather in relation to the science of climate change, and to look at the projected changes in climate, with a special emphasis on the issues and remaining uncertainties affecting our future.

5.2 Our Changing Climate

Climate is defined as long-term averages and variations in weather measured over multiple decades. The Earth's climate system includes the land surface, atmosphere, oceans, and ice. Scientists and engineers from around the world have compiled the evidence that the climate is changing, changing much more rapidly than tends to occur naturally (by a factor of ten according to some studies), and that it is changing because of human activities; these conclusions are based on observations from satellites, weather balloons, thermometers at surface stations, ice cores, and many other types of observing systems that monitor the Earth's weather and climate. A wide variety of independent observations give a consistent picture of a warming world. There are many indicators of this change, not just atmospheric surface temperature. For example, ocean temperatures are also rising, sea level is rising, Arctic sea ice is decreasing, most glaciers are decreasing, Greenland and Antarctic land ice is decreasing, and atmospheric humidity is increasing.

Temperatures at the surface, in the troposphere (the active weather layer extending up to about 5–10 miles above the ground), and in the oceans have all increased over recent decades. Consistent with our scientific understanding, the largest increases in temperature are occurring closer to the poles, especially in the Arctic (this is primarily related to ice-albedo feedback that as snow and ice decreases, the exposed surface will absorb more solar radiation rather than reflect it back to space). Snow and ice cover have decreased in most areas of the world. Atmospheric water vapor (H_2O) is increasing in the lower atmosphere, because a warmer atmosphere can hold more water. Sea levels are also increasing. All of these findings are based on observations.

As seen in Fig. 5.1, global annual average temperature (as measured over both land and oceans) has increased by more than 0.8 °C (1.5 °F) since 1880 (through 2012). While there is a clear long-term global warming trend, some years do not show a temperature increase relative to the previous year, and some years show greater changes than others. These year-to-year fluctuations in temperature are related to natural processes, such as the effects of El Niños, La Niñas, and the effects of volcanic eruptions. Globally, natural variations can be as large as human-induced climate change over timescales of up to a few decades. However, changes in climate at the global scale observed over the past 50 years are far larger than can be accounted for by natural variability (IPCC 2013). At the local to regional scale, changes in climate can be influenced by natural variability for multiple decades (Deser et al. 2012).

While there has been widespread warming over the past century, not every region has warmed at the same pace (Fig. 5.2). A few regions, such as the North Atlantic Ocean and some parts of the U.S. Southeast, have even experienced cooling over the last century as a whole, though they have warmed over recent decades. This is due to the stronger influence of internal variability over smaller geographic regions and shorter time scales. Warming during the first half of the last century occurred mostly in the Northern Hemisphere. The last three decades have

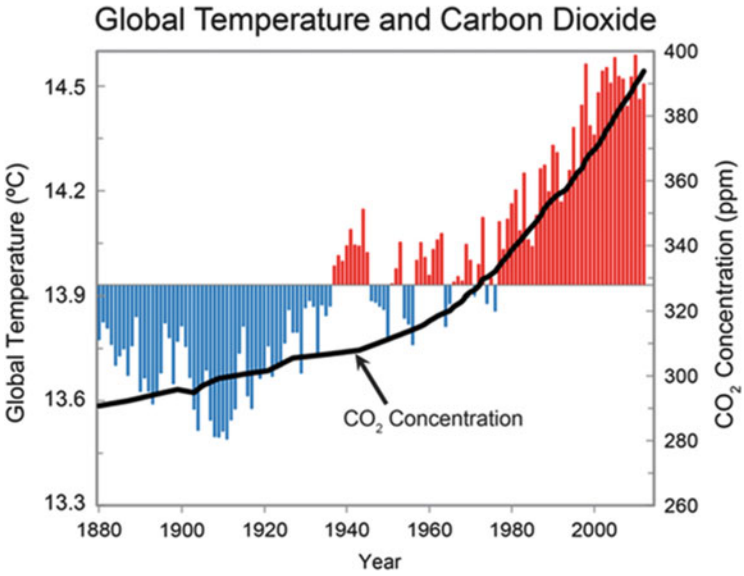

Fig. 5.1 Changes in observed globally-averaged temperature since 1880. *Red bars* show temperatures above the long-term average, and *blue bars* indicate temperatures below the long-term average. The *black line* shows the changes in atmospheric carbon dioxide (CO_2) concentration in parts per million (ppm) over the same time period (Melillo et al. 2014; temperature data from NOAA National Climate Data Center)

seen greater warming in response to accelerating increases in heat-trapping gas concentrations, particularly at high northern latitudes, and over land as compared to the oceans. These findings are not surprising given the larger heat capacity of the oceans leading to land-ocean differences in warming and the ice-albedo feedback (melting of ice leading to a higher surface albedo and more solar absorption) leading to larger warming at higher latitudes. As a result, land areas can respond to the changes in climate much more rapidly than the ocean areas even though the forcing driving a change in climate occurs equally over land and the oceans.

Even if the surface temperature had never been measured, scientists could still conclude with high confidence that the global temperature has been increasing because multiple lines of evidence all support this conclusion. Figure 5.3 shows a number of examples of the indicators that show the climate on Earth is changing very rapidly over the last century. Temperatures in the lower atmosphere and oceans have increased, as have sea level and near-surface humidity. Basic physics tells us that a warmer atmosphere can hold more water vapor; this is exactly what is measured from the satellite data showing that humidity is increasing. Arctic sea ice, mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. Over 90 % of the glaciers in the world are decreasing at very significant rates. The amount of ice on the largest masses of ice on our planet, on Greenland and Antarctica, are decreasing. As with temperature, many scientists and associated research groups have analyzed each of these indicators and come to the same

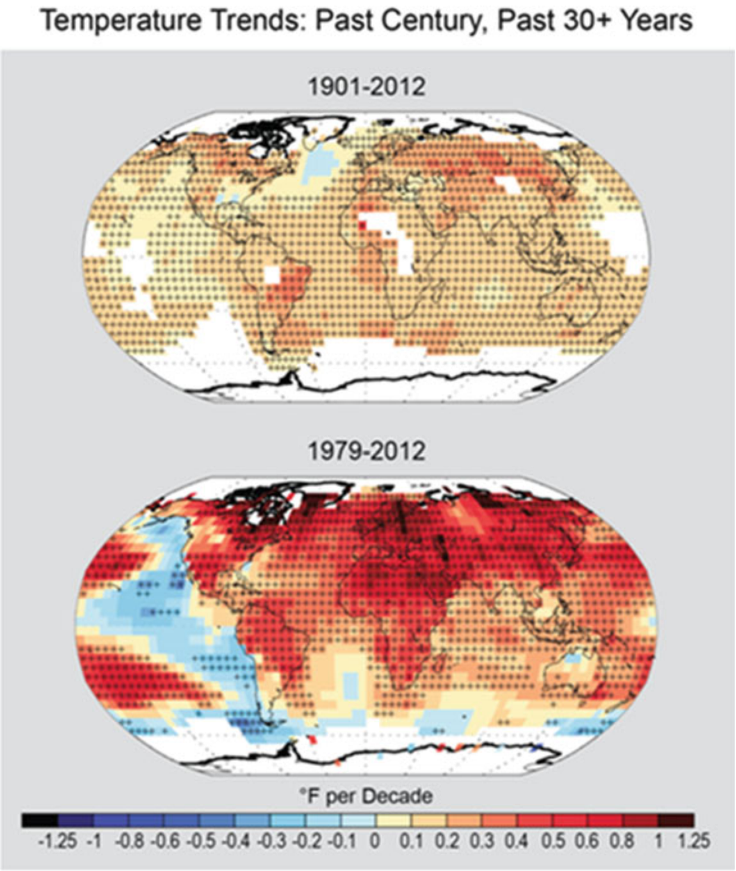

Fig. 5.2 Surface temperature trends for the period 1901–2012 (*top*) and 1979–2012 (*bottom*) from NOAA National Climate Data Center's surface temperature product. Updated from Vose et al. (2012). From Melillo et al. (2014)

conclusion: all of these changes paint a consistent and compelling picture of a warming world.

Precipitation is perhaps the most societally relevant aspect of the hydrological cycle and has been observed over global land areas for over a century. However, spatial scales of precipitation are small (e.g., it can rain several inches in Washington, DC, but not a drop in nearby Baltimore) and this makes interpretation of the point-measurements difficult. Based upon a range of efforts to create global averages, there does not appear to have been significant changes in globally averaged precipitation since 1900 (although as we will discuss later there has been a significant trend for an increase in precipitation coming as larger events). However, in looking at total precipitation there are strong geographic trends including a likely increase in precipitation in Northern Hemisphere mid-latitude

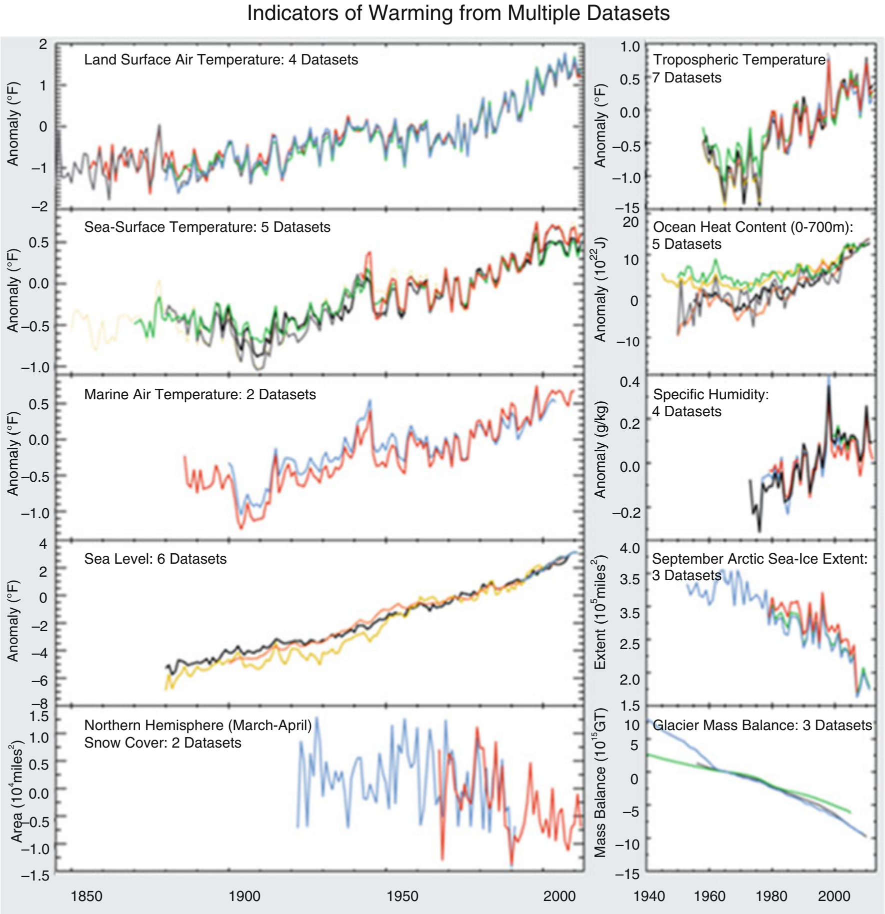

Fig. 5.3 Observed changes, as analyzed by many independent groups in different ways, of a range of climate indicators. All of these are in fact changing as expected in a warming world. Further details underpinning this diagram can be found at http://www.ncdc.noaa.gov/bams-state-of-the-climate/ (From Melillo et al. 2014)

regions taken as a whole (see Fig. 5.4). Stronger trends are generally found over the last four decades. In general, the findings are that wet areas are getting wetter and dry areas are getting drier, consistent with an overall intensification of the hydrological cycle in response to global warming (IPCC 2013).

It is well known that warmer air can contain more water vapor than cooler air. Global analyses show that the amount of water vapor in the atmosphere has in fact increased over both land and oceans. Climate change also alters dynamical characteristics of the atmosphere that in turn affect weather patterns and storms. At mid-latitudes, there is an upward trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms. Locally, natural variations can also be important. In contrast, the subtropics are generally tending to have less overall rainfall and more droughts. Nonetheless, many areas show an increasing tendency

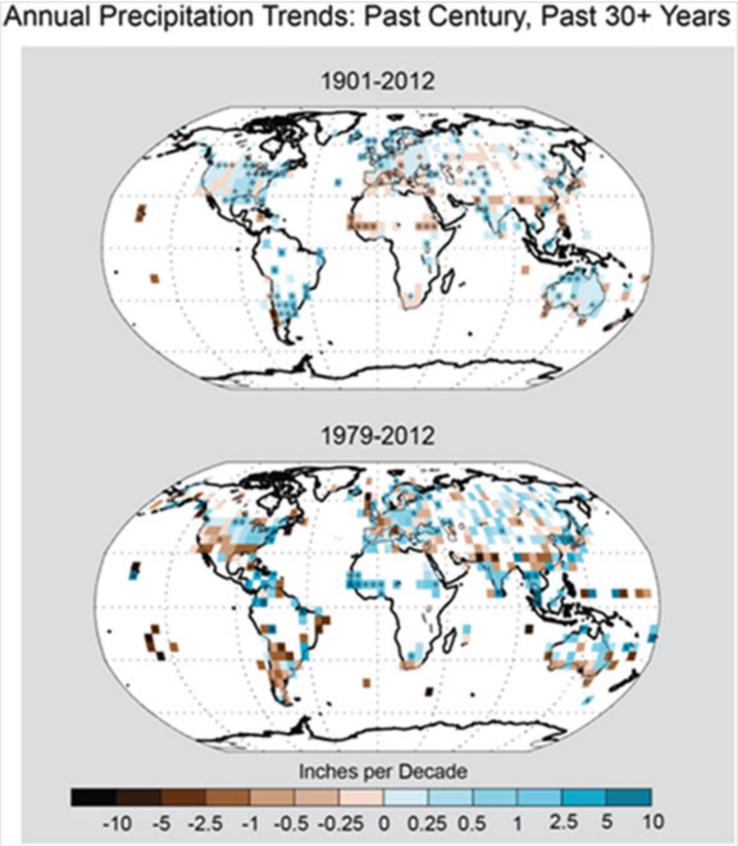

Fig. 5.4 Global precipitation trends for the period 1901–2012 (*top*) and 1979–2012 (*bottom*). Based on date from NOAA NCDC. From Melillo et al. (2014)

for larger rainfall events when it does rain (Janssen et al. 2014; Melillo et al. 2014; IPCC 2013).

5.3 Attribution: Why Is the Climate Changing?

Over the last five decades, natural drivers of climate such as solar forcing and volcanoes would actually have led to a slight cooling. Natural drivers cannot explain the observed warming over this period. The majority of the warming can only be explained by the effects of human influences (IPCC 2013; Gillett et al. 2012; Santer et al. 2013; Stott et al. 2010), especially the emissions from burning fossil fuels (coal, oil, and natural gas), and from changes in land use, such as deforestation. As a result of human activities, atmospheric concentrations of various gases and particles are changing, including those for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and particles such as black carbon (soot), which has a warming influence, and sulfates, which have an overall cooling influence. The most important changes are occurring in the concentration of CO_2; it's atmospheric concentration recently reached 400 ppm (400 molecules per one million molecules of air; this small amount is important because of the heat-trapping ability of CO_2). Four hundred parts per million of CO_2 has not been seen on Earth for over one million years, well before the appearance of humans. The increase in CO_2 over the last several 100 years is almost entirely due to burning of fossil fuels and land use change (IPCC 2013).

The conclusion that human influences are the primary driver of recent climate change is based on multiple lines of independent evidence. The first line of evidence is our fundamental understanding of how certain gases trap heat (these so-called greenhouse gases include H_2O, CO_2, CH_4, N_2O, and some other gases and particles that can all absorb the infrared radiation emitted from the Earth that otherwise would go to space), how the climate system responds to increases in these gases, and how other human and natural factors influence climate.

The second line of evidence is from reconstructions of past climates using evidence such as tree rings, ice cores, and corals. These show that the change in global surface temperatures over the last five decades are clearly unusual, and outside the range of natural variability. These analyses show that the last decade (2000–2009) was warmer than any time in at least the last 1300 years and perhaps much longer (IPCC 2013; PAGES 2K Consortium 2013; Mann et al. 2008).

Globally averaged surface air temperature has slowed its rate of increase since the late 1990s. This is not in conflict with our basic understanding of global warming and its primary cause. The decade of 2000–2009 was still the warmest decade on record. In addition, global surface air temperature does not always increase steadily and can be influenced by natural variability on the scale of a few decades (for further discussion, see IPCC 2013; Melillo et al. 2014; the explanation for the slowdown in global surface temperature is further discussed in a special issue of Nature from March 2014). Other climate change indicators, like the decrease in Arctic sea ice and sea level rise, have not seen the same slowdown.

The third line of evidence comes from using climate models to simulate the climate of the past century, separating the human and natural factors that influence climate. As shown in Fig. 5.5, when the human factors are removed, these models show that solar and volcanic activity would have tended to slightly cool the earth, and other natural variations are too small to explain the amount of warming. The range of values account for the range of results from the 20+ different models from around the world used in these analyses for the international climate assessment (IPCC 2013). Only when the human influences are included do the models reproduce the warming observed over the past 50 years.

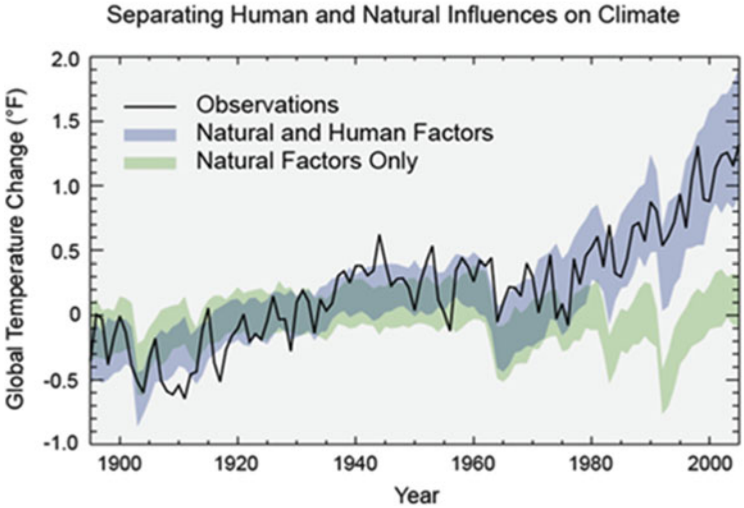

Fig. 5.5 Observed global average changes (*black line*), and model simulations using only changes in natural factors (solar and volcanic) in *green*, and with the addition of human-induced emissions (*blue*). Climate changes since 1950 cannot be explained by natural factors or variability, and can only be explained by human factors (Figure source: adapted from Huber and Knutti 2011). From Melillo et al. (2014)

5.4 Trends in Extreme Weather Events

A series of studies by Kunkel et al. (2013), Peterson et al. (2013), Vose et al. (2014), and Wuebbles et al. (2014a), along with many other journal papers, has led to a collective assessment regarding changes in various weather extremes relative to the changing climate. The adequacy of the existing data to detect trends in severe weather events was examined relative to the current scientific ability to understand what drives those trends, i.e., how well the physical processes are understood, and thus how the extremes are expected to change in the future. This assessment shows that there are some events, such as those relating to temperature and precipitation extremes, where there is strong understanding of the trends and the underlying causes of the changes. The adequacy of data for floods, droughts, and extra-tropical cyclones to detect trends is also high, but there is only medium understanding of the underlying cause of their long-term changes. There is also medium understanding of the observed trends and cause of changes in hurricanes and in snow events. For some events, such as strong winds, hail, ice storms, and tornadoes, there is currently insufficient understanding of the trends or of the causes for the trends to make strong conclusions about these events in a changing climate. These findings also correlate well with global analyses of climate extremes (IPCC 2012, 2013).

Changing trends in some types of extreme weather events have been observed in recent decades. Modeling studies indicate that these trends are consistent with the changing climate. Much of the world is being affected by changing trends in extreme events, including increases in the number of extremely hot days, less extreme cold days, more precipitation events coming as unusually large precipitation, and more floods in some regions and more drought in others (Min et al. 2011; IPCC 2012, 2013; Zwiers et al. 2013; Melillo et al. 2014; Wuebbles et al. 2014a, b). High impact, large-scale extreme events are complex phenomena involving various factors that come together to create a "perfect storm." Such extreme weather obviously does occur naturally. However, the influence of human activities on global climate is altering the frequency and/or severity of many of these events. Observed trends in extreme weather events, such as more hot days, less cold days, and more precipitation coming as extreme events, are expected to continue and to intensify over this century.

In most of the United States over the last couple of decades, the heaviest rainfall events have become more frequent (e.g., see Fig. 5.6) and the amount of rain falling in very heavy precipitation events has been significantly above average. This increase has been greatest in the Northeast, Midwest, and upper Great Plains. Similar findings are being found in many other parts of the world. Since basic physics tells us that a warmer atmosphere should generally hold more water vapor,

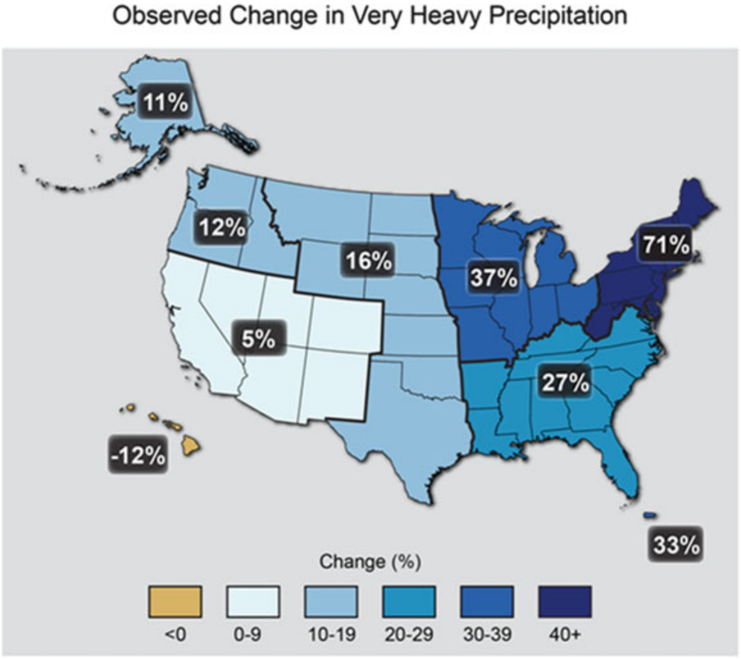

Fig. 5.6 Percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1 % of all daily events) from 1958 to 2012 for each region of the continental U.S. These trends are larger than natural variations for the Northeast, Midwest, Puerto Rico, Southeast, Great Plains, and Alaska. The trends are not larger than natural variations for the Southwest, Hawai'i, and the Northwest. The changes shown in this figure are calculated from the beginning and end points of the trends for 1958–2012. From Melillo et al. (2014)

this finding is not so surprising. Analyses indicate that these trends will continue (Janssen et al. 2014; Melillo et al. 2014; Wuebbles et al. 2014a, b).

The meteorological situations that cause heat waves are a natural part of the climate system. Thus the timing and location of individual events may be largely a natural phenomenon, although even these may be affected by human-induced climate change (Trenberth and Fasullo 2012). However, there is emerging evidence that most of the increasing heat wave severity over our planet is likely related to the changes in climate, with a detectable human influence for major recent heat waves in the U.S. (Rupp et al. 2012; Duffy and Tebaldi 2012; Meehl et al. 2009), Europe (Stott et al. 2010; Trenberth 2011), and Russia (Christidis et al. 2011). As an example, the summer 2011 heat wave and drought in Oklahoma and Texas, which cost Texas an estimated $8 billion in agricultural losses, was primarily driven by precipitation deficits, but the human contribution to climate change approximately doubled the probability that the heat was record-breaking (Hoerling et al. 2013). So while an event such as this Texas heat wave and drought could be triggered by a naturally occurring event such as a deficit in precipitation, the chances for record-breaking temperature extremes have increased and will continue to increase as the global climate warms. Generally, the changes in climate are increasing the likelihood for these types of severe events.

In the tropics, the most important types of storms are tropical cyclones, referred to as hurricanes when they occur in the Atlantic Ocean. Over the 40 years of satellite monitoring, there has been a shift toward stronger hurricanes in the Atlantic, with fewer smaller (category one and two) hurricanes and more intense (category four and five) hurricanes. There has been no significant trend in the global number of tropical cyclones (IPCC 2012, 2013) nor has any trend been identified in the number of U.S. landfalling hurricanes (Melillo et al. 2014).

Trends remain uncertain in some types of severe weather, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, but such events are under scrutiny to determine if there is a climate change influence. Initial studies do suggest that tornadoes could get more intense in the coming decades (Diffenbaugh et al. 2013).

5.5 Climate Projections: Temperature and Precipitation

On the global scale, climate model simulations show consistent projections of future conditions under a range of emissions scenarios (that depend on assumptions of population change, economic development, our continued use of fossil fuels, changes in other human activities, and other factors). For temperature, all models show warming by late this century that is much larger than historical variations nearly everywhere (see Fig. 5.7). For precipitation, models are in complete agreement in showing decreases in precipitation in the subtropics and increases in precipitation at higher latitudes. As mentioned earlier, extreme weather events

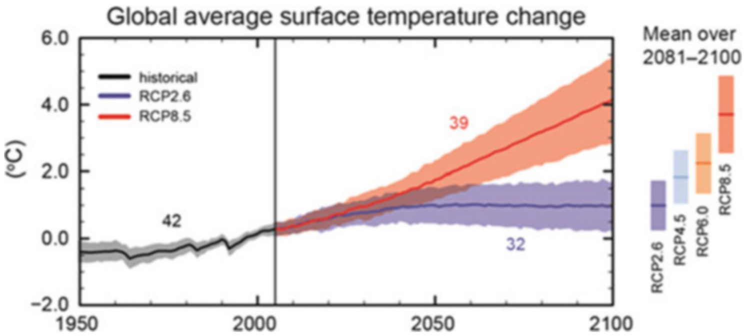

Fig. 5.7 Multi-model simulated time series from 1950 to 2100 for the change in global annual mean surface temperature relative to 1986–2005 for a range of future emissions scenarios that account for the uncertainty in future emissions from human activities [as analyzed with the 20+ models from around the world used in the most recent international assessment (IPCC 2013)]. The mean and associated uncertainties [1.64 standard deviations (5–95 %) across the distribution of individual models (*shading*)] based on the averaged over 2081–2100 are given for all of the RCP scenarios as colored vertical bars. The numbers of models used to calculate the multi-model mean is indicated [(**a**) from IPCC (2103) Summary for Policymakers]

associated with extremes in temperature and precipitation are likely to continue and to intensify.

Choices made now and in the next few decades about emissions from fossil fuel use and land use change will determine the amount of additional future warming over this century and beyond. Global emissions of CO_2 and other heat-trapping gases continue to rise. How much climate will change over this century and beyond depends primarily on: (1) human activities and resulting emissions; and (2) how sensitive the climate is to those changes (that is, the response of global temperature to a change in radiative forcing caused by human emissions). Uncertainties in how the economy will evolve, what types of energy will be used, or what our cities, buildings, or cars will look like in the future are all important and limit the ability to project future changes in climate. Scientists can, however, develop scenarios—plausible projections of what might happen, under a given set of assumptions. These scenarios describe possible futures in terms of population, energy sources, technology, heat-trapping gas emissions, atmospheric levels of carbon dioxide, and/or global temperature change.

A certain amount of climate change is already inevitable due to the build-up of CO_2 in the atmosphere from human activities (although there is a rapid exchange of CO_2 with the biosphere, the eventual lifetime for atmospheric CO_2 is dependent on removal to the deep ocean). The Earth's climate system, particularly the oceans, tends to lag behind changes in atmospheric composition by decades, and even centuries due to the large heat capacity of the oceans and other factors. Another 0.2–0.3 °C (about 0.5 °F) increase is expected over the next few decades (Matthews and Zickfeld 2012) although natural variability could still play an important role over this time period (Hawkins and Sutton 2011). The higher the human-related emissions of CO_2 and other heat-trapping gases over the coming decades, the higher the resulting changes expected by mid-century and beyond. By the second half of the century, however, scenario uncertainty (that is, uncertainty about what will be the level of emissions from human activities) becomes increasingly dominant in determining the magnitude and patterns of future change, particularly for temperature-related aspects (Hawkins and Sutton 2009, 2011).

As seen in Figs. 5.7 and 5.8 for a range of scenarios varying from assuming strong continued dependence on fossil fuels in energy and transportation systems over the twenty-first century (scenario RCP8.5) to assuming major mitigation actions (RCP2.6), global surface temperature change for the end of the twenty-first century is *likely* to exceed an increase of 1.5 °C (2.7 °F) relative to 1850–1900 for all projections except for the RCP2.6 scenario (IPCC 2013). Note that the RCP2.6 scenario is much lower than the other scenarios examined because it not only assumes significant mitigation to reduce emissions, but it also assumes that technologies are developed that can achieve net negative carbon dioxide emissions (removal of CO_2 from the atmosphere) before the end of the century.

A number of research studies have examined the potential criteria for dangerous human interferences in climate where it will be difficult to adapt to the changes in climate without major effects on our society (e.g., Hansen et al. 2007). Most of these studies have concluded that an increase in globally average temperature of roughly 1.5 °C (2.7 °F) is an approximate threshold for dangerous human interferences with the climate system (see IPCC 2013, 2014 for further discussion), but this threshold is not exact and the changes in climate are geographically diverse and impacts are sector dependent, so there really is no defined threshold by when dangerous interferences is actually reached.

The warming and other changes in the climate system will continue beyond 2100 under all RCP scenarios, except for a leveling of temperature under RCP2.6. In

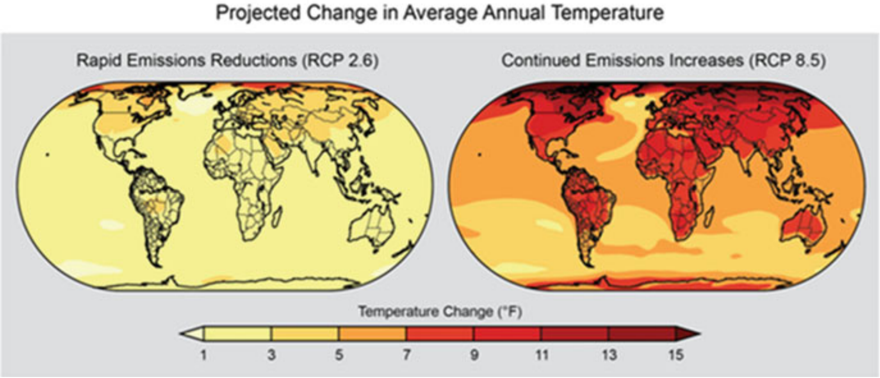

Fig. 5.8 Projected change in average annual temperature over the period 2071–2099 (compared to the period 1971–2000) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gases (RCP 2.6), and a higher scenario that assumes continued increases in emissions (RCP 8.5). From Melillo et al. (2014)

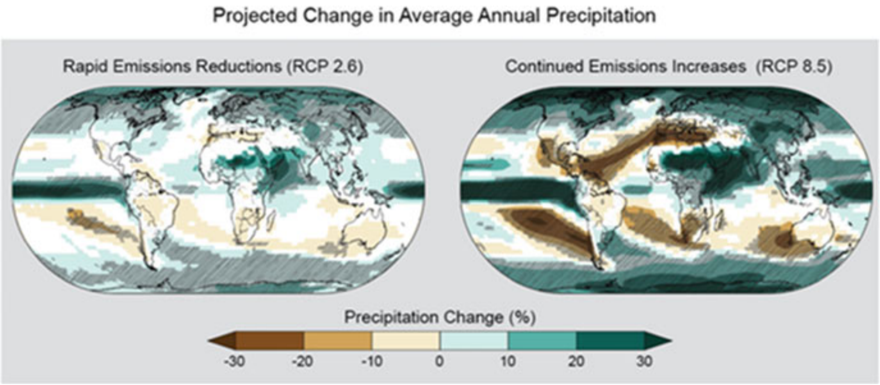

Fig. 5.9 Projected change in average annual precipitation over the period 2071–2099 (compared to the period 1971–2000) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gasses (RCP 2.6), and a higher scenario that assumes continued increases in emissions (RCP 8.5). Hatched areas indicate confidence that the projected changes are significant and consistent among models. *White* areas indicate that the changes are not projected to be larger than could be expected from natural variability. In general, northern parts of the U.S. (especially the Northeast and Alaska) are projected to receive more precipitation, while southern parts (especially the Southwest) are projected to receive less. From Melillo et al. (2014)

addition, it is fully expected that the warming will continue to exhibit inter-annual-to-decadal variability and will not be regionally uniform.

Projections of future changes in precipitation show small increases in the global average but substantial shifts in where and how precipitation falls (see Fig. 5.9). Generally, areas closest to the poles are projected to receive more precipitation, while the dry subtropics (the region just outside the tropics, between 23° and 35° on either side of the equator) will generally expand toward the poles and receives less rain. Increases in tropical precipitation are projected during rainy seasons (such as monsoons), especially over the tropical Pacific. Certain regions, including the western U.S. [especially the Southwest (Melillo et al. 2014) and the Mediterranean (IPCC 2013)], are presently dry and are expected to become drier. The widespread trend of increasing heavy downpours is expected to continue, with precipitation becoming more intense (Boberg et al. 2009; Gutowski et al. 2007; Sillmann et al. 2013). The patterns of the projected changes of precipitation do not contain the spatial details that characterize observed precipitation, especially in mountainous terrain, because of model uncertainties and their current spatial resolution (IPCC 2013).

5.6 Climate Projections: Extreme Weather Events

As mentioned earlier, some areas both in the U.S. and throughout the world are already experiencing climate-related disruptions, particularly due to extreme weather events. These trends are likely to continue throughout this century.

Existing research indicate the following trends over the coming decades (see Melillo et al. 2014, or IPCC 2013 for more details):

- It is likely that over the coming decades the frequency of warm days and warm nights will increase in most land regions, while the frequency of cold days and cold nights will decrease. As a result, an increasing tendency for heat waves is likely in many regions of the world.
- Some regions are likely to see an increasing tendency for droughts while others are likely to see an increasing tendency for floods. This roughly corresponds to the wet getting wetter and the dry getting drier.
- It is likely that the frequency and intensity of heavy precipitation events will increase over land. These changes are primarily driven by increases in atmospheric water vapor content, but also affected by changes in atmospheric circulation.
- Tropical storm (hurricane)-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.
- Initial studies also suggest that tornadoes are likely to become more intense.
- For some types of extreme events, like wind storms, and ice and hail storms, there is too little understanding currently of how they will be affected by the changes in climate.

5.7 Sea Level Rise and Ocean Acidification

After at least 2000 years of little change, the world's sea level rose by roughly 0.2 m (8 in.) over the last century, and satellite data provide evidence that the rate of rise over the past 20 years has roughly doubled. Around the world, many millions of people and many assets related to energy, transportation, commerce, and ecosystems are located in areas at risk of coastal flooding because of sea level rise and storm surge. Sea level is rising because ocean water expands as it heats up and because water is added to the oceans from melting glaciers and ice sheets.

Sea level is projected to rise an additional 0.3–1.2 m (1–4 ft) in this century (see Fig. 5.10; Melillo et al. 2014; similar findings in IPCC 2013). The best estimates for the range of sea level rise projections for this century remain quite large; this may be due in part to what emissions scenario we follow, but more importantly it depends on just how much melting occurs from the ice on large land masses, especially from Greenland and Antarctica. Recent projections show that for even the lowest emissions scenarios, thermal expansion of ocean waters (Yin 2012) and the melting of small mountain glaciers (Marzeion et al. 2012) will result in 11 in. of sea level rise by 2100, even without any contribution from the ice sheets in Greenland and Antarctica. This suggests that about 0.3 m (1 ft) of global sea level rise by 2100 is probably a realistic low end. Recent analyses suggest that 1.2 m (4 ft) may be a reasonable upper limit (Rahmstorf et al. 2012; IPCC 2013; Melillo et al. 2014). Although scientists cannot yet assign likelihood to any

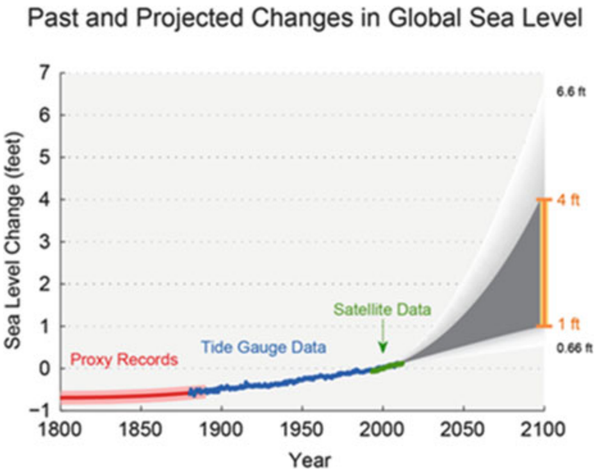

Fig. 5.10 Estimated, observed, and projected amounts of global sea level rise from 1800 to 2100, relative to the year 2000. Estimates from proxy data (for example, based on sediment records) are shown in *red* (1800–1890, *pink band* shows uncertainty), tide gauge data in *blue* for 1880–2009 (Church and White 2011; Church et al. 2011) and satellite observations are shown in *green* from 1993 to 2012 (Nerem et al. 2010). The future scenarios range from 0.66 to 6.6 ft in 2100 (Parris et al. 2012). These scenarios are not based on climate model simulations, but rather reflect the range of possible scenarios based on scientific studies. The *orange line* at *right* shows the currently projected range of sea level rise of 1–4 ft by 2100, which falls within the larger risk-based scenario range. The large projected range reflects uncertainty about how glaciers and ice sheets will react to the warming ocean, the warming atmosphere, and changing winds and currents. As seen in the observations, there are year-to-year variations in the trend. From Melillo et al. (2014)

particular scenario, in general, higher emissions scenarios would be expected to lead to higher amounts of sea level rise.

Because of the warmer global temperatures, sea level rise will continue beyond this century. Sea levels will likely continue to rise for many centuries at rates equal to or higher than that of the current century. Many millions of people live within areas than can be affected by the effects of storm surge within a rising sea level. The Low Elevation Coastal Zone (less than 10 m elevation) constitutes 2 % of the world's land area but contains 10 % of the world's population based on year 2000 estimates (McGranahan et al. 2007).

As CO_2 concentrations build up in the atmosphere, some of this CO_2 is dissolving into the oceans where it reacts with seawater to form carbonic acid, lowering ocean pH levels ("acidification") and threatening a number of marine ecosystems (Doney et al. 2009). The oceans currently absorb about a quarter of the CO_2 humans produce every year (Le Quéré et al. 2009). Over the last 250 years, the oceans have absorbed 560 billion tons of CO_2, increasing the acidity of surface waters by 30 % (Melillo et al. 2014). Although the average oceanic pH can vary on interglacial timescales (Caldeira and Wickett 2003), the current observed rate of change is roughly 50 times faster than known historical change (Hönisch et al. 2012; Orr 2011). Regional factors such as coastal upwelling (Feely et al. 2008), changes in discharge rates from rivers and glaciers (Mathis et al. 2011) sea ice loss (Yamamoto-Kawai et al. 2009), and urbanization (Feely et al. 2010) have created "ocean acidification hotspots" where changes are occurring at even faster rates.

The acidification of the oceans has already caused a suppression of carbonate ion concentrations that are critical for marine calcifying animals such as corals, zooplankton, and shellfish. Many of these animals form the foundation of the marine food web. Today, more than a billion people worldwide rely on food from the ocean as their primary source of protein. Ocean acidification puts this important resource at risk.

Projections indicate that in a higher emissions scenario (that assume continuing use of fossil fuels), ocean pH could be reduced from the current level of 8.1 to as low as 7.8 by the end of the century (Orr et al. 2005). Such large rapid changes in ocean pH have probably not been experienced on the planet for the past 100 million years, and it is unclear whether and how quickly ocean life could adapt to such rapid acidification (Hönisch et al. 2012). The potential impact on the human source of food from the oceans is also unclear.

5.8 Conclusions

Observations show that climate change is happening, that it is happening rapidly, and that it is primarily due to human activities, especially the emissions occurring from our dependence on fossil fuels. There is an increasing level of risks to society from severe weather events and from sea level rise.

Large reductions in global emissions of heat-trapping gases would reduce the risks of some of the worst impacts of climate change. Meanwhile, global emissions are still rising and are on a path to be even higher than the high emissions scenario examined in this study.

As the impacts of climate change are becoming more prevalent, humanity face choices. Especially because of past emissions of long-lived heat-trapping gases, some additional climate change and related impacts are now unavoidable. This is due to the long-lived nature of many of these gases, as well as the amount of heat absorbed and retained by the oceans and other responses within the climate system. The amount of future climate change, however, will still largely be determined by choices society makes about emissions. Lower emissions of heat-trapping gases and particles mean less future warming and less-severe impacts; higher emissions mean more warming and more severe impacts.

There are a number of areas where improved scientific information or understanding would enhance the capacity to estimate future climate change impacts. For example, knowledge of the mechanisms controlling the rate of ice loss in Greenland and Antarctica is limited, making it difficult for scientists to narrow the range of expected future sea level rise. Improved understanding of ecological and social responses to climate change is needed, as is understanding of how ecological and social responses will interact (Melillo et al. 2014).

Adaptation to the changing climate is not an option; our choice is to prepare proactively or to respond to events after they happen. Proactively preparing for climate change can reduce impacts while also facilitating a more rapid and efficient response to changes as they happen. Such efforts are beginning in the U.S. and other parts of the world, to build adaptive capacity and resilience to climate change impacts. Using scientific information to prepare for climate changes in advance can provide economic opportunities, and proactively managing the risks can reduce impacts and costs over time.

The choices we make will not only affect us, they will affect our children, our grandchildren, and future generations.

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Chapter 6
Climate Change and Natural Hazards

Douglas MacLean

Abstract Climate change is happening, and the consequences are likely to be bad. If we—the people and nations of the world—fail to take action soon to address its causes and mitigate its effects, the consequences may be very bad. What should we do? Bill McKibben calls this "the most important question that there ever was," and many of the scientists who study the issue have described it as one of the most difficult and important challenges that human civilization has confronted. (The quote comes from a tribute McKibben gave for James Hansen. See Justin Gillis, "Climate Maverick to Retire from NASA," *The New York Times*, April 1, 2013.) My goal in this chapter is to examine some of the moral dimensions of the problem. These turn out to be philosophically complicated and challenging. As a practical matter, the causes and consequences of climate change have unprecedented spatial and temporal scope. Others who have written on climate change ethics have pointed out that these facts about scope make the problem difficult to think about clearly. I will describe these issues, but my goal is to try to explain how the spatial and temporal dimensions interact to create a unique moral dilemma. There are ample grounds in this analysis for pessimism, but I believe it also suggests how we can most usefully think about constructive responses to McKibben's question.

6.1 Knowledge and Uncertainty

Although the goal of this chapter is to analyze philosophical and moral issues, I need to describe the context or background that frames the problem. This material will be familiar to many readers, but it reveals the assumptions that I bring to the discussion. I start with a brief a summary of what we know about climate change. Basically, we now know a lot about what has happened in the past, and this knowledge allows us both to make some general predictions about the future with a high degree of confidence and to explain the nature of the uncertainties involved when we try to make more specific predictions.

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Climate science is complex, but the fundamental chemical and physical facts are well understood. The sun's rays reach the Earth and warm it. Most of the rays are reflected back into space, but certain gases in the atmosphere trap some of the longer, infrared rays, and this warms the atmosphere. The same process occurs in a greenhouse when the glass or plastic top traps infrared rays and keeps the greenhouse warm. Hence, we call this process the 'greenhouse effect,' and we call these gases 'greenhouse gases (GHGs). The greenhouse effect was first hypothesized by James Fourier in 1824 and confirmed toward the end of the nineteenth century by John Tyndall. It explains why the Earth's atmosphere remains warm enough to support life.[1]

The principal greenhouse gas, by concentration if not by potency, is CO_2, which is released into the atmosphere through the natural decay of biomass, but also when we burn fossil fuels—for example, when we drive automobiles, when we use oil, coal, gas, or wood to heat our homes, or when we burn these fuels to produce electricity. In 1896 the Swedish chemist Svante Arrhenius hypothesized that human activity that produced CO_2 could add to the greenhouse effect, but he thought this addition would be relatively benign compared to the warming caused by other natural sources of GHG emissions. It wasn't until the mid-twentieth century that scientists began to notice that anthropogenic GHG emissions have been increasing at an alarming rate, and that atmospheric concentrations of GHGs were reaching unprecedented levels, causing a noticeable rise in the Earth's average surface temperature. No climate models existed then to predict the consequences of rising average temperature, and scientists were just beginning to drill and save ice core samples from the Antarctic ice sheets and mountain glaciers, which gave them data on GHG concentrations and climate variations in the past. Although climate science was in its infancy at the time, researchers started expressing concerns about the effects of anthropogenic GHG emissions. A report by Lyndon Johnson's Science Advisory Committee in 1965, for example, mentioned the greenhouse effect and warned that, "Man is unwittingly conducting a vast geophysical experiment."[2]

Over the past half century climate science continued to advance, and we now have data from a number of sources that give us a clear picture of what has happened so far. GHG concentrations in the atmosphere have increased 40 % since 1800, that is, since the beginning of the industrial revolution. This concentration recently surpassed 400 parts per million in the northern hemisphere, a level unprecedented in three million years. The greenhouse effect tells us that increased concentrations of GHGs should cause average temperatures at the Earth's surface to rise, and this has also happened. The average surface temperature has increased by 1.4 °F since 1900; the 30-year period between 1983 and 2013 is probably the warmest such period in over 800 years; and 2014 was the hottest year on record. These facts about GHG concentrations and their effects on global warming are

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[1] For an account of the history of climate science, see Spencer Waert, *The discovery of Global Warming*, Harvard University Press, 2003.

[2] Waert, op. cit.

beyond reasonable dispute, as is the claim that human activity is responsible for much of the increased concentration of GHGs over the past two centuries.

Similarly, some of the further effects of global warming are also beyond doubt. One of these effects is a rise in sea level. Natural events, such as the processes that cause land masses to rise and sink, produce changes in sea level, but a warming climate also causes the seas to rise, because an increase in temperature causes water volume to expand and glaciers to melt. Since 1901, the overall rise in sea level is about 8 in., and most climate models predict that if GHG emissions continue to increase at their current rate, the seas will rise by another 1.5–3 ft by the end of this century.

Almost as certain are some further predicted effects of global warming. A rising average surface temperature causes the Earth's lower atmosphere to become warmer and moister, which creates more potential energy for storms and other severe weather events. We should therefore expect more severe weather events to occur in many regions of the Earth. As one recent report explains, "Consistent with theoretical expectations, heavy rainfall and snowfall events (which increase the risk of flooding) and heat waves are generally becoming more frequent. . .Basic physical understanding and model results suggest that the strongest hurricanes (when they occur) are likely to become more intense and possibly larger in a warmer, moister atmosphere over the oceans."[3]

Climate science is enormously complex. It requires input from many disciplines and relies on sophisticated computer models to integrate vast amounts of data. When it comes to predicting the future, these models are riddled with different kinds of uncertainties, which can be frustrating to lay people (like myself) who are trying to understand what is going on and what we should expect. One uncertainty has to do with predictions of increased frequency of severe weather events that also occur "naturally," that is to say, in ways that are not necessarily caused by climate change or human activity. This uncertainty makes it difficult, if not impossible, to know whether any particular unusually severe hurricane, flood, or drought is the result of climate change. In other words, predictions about severe weather events are irreducibly statistical. Another source of uncertainty is that climate predictions depend on many assumptions about what will happen in the future, including especially assumptions about human activity. These assumptions are also necessarily uncertain and need to be continually updated and modified.

Given the complexities of the science and the nature of the uncertainties involved, are we really justified in claiming to know that climate change is happening and will get worse if we don't change our behavior? Here, as in many areas of life, we inevitably must rely heavily on the judgment of experts. The most authoritative source of information about the findings of climate science is the Intergovernmental Panel on Climate Change (IPCC), a group of hundreds of

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[3] *Climate Change: Evidence & Causes: An Overview from the Royal Society and the U.S. National Academy of Sciences*, April 2014, available at http://dels.nas.edu/resourcese/static-assets/exec-office-other/climate-change-full.pdf, p. 5.

scientists and government officials representing 195 countries. The IPCC was organized by the United Nations Environmental Program and the World Meteorological Organization in 1988 to issue periodic reports on the state of scientific knowledge about climate change and its impacts. Because of its large and diverse membership and its bureaucratic structure, IPCC reports are constrained to describe only conclusions that are supported by a consensus of its members. This introduces a bias toward conservatism and caution that participants in the process are quick to acknowledge (often with some frustration).

The IPCC's Fifth Assessment Report, a massive document issued in stages in 2013–2014, nevertheless leaves no doubt that anthropogenic climate change is happening, and its effects are already being felt.[4] These conclusions are echoed in other reports on the consensus judgments of climate scientists. For example, in May 2014 the White House published the U.S. government's third National Climate Assessment (NCA), which was a product of thirteen federal agencies and 300 experts, guided by a 60-member Federal Advisory Committee and reviewed by the public and other experts. This report explains in its overview that:

> Over recent decades, climate science has advanced significantly. Increased scrutiny has led to increased certainty that we are now seeing impacts associated with human-induced climate change. With each passing year, the accumulating evidence further expands our understanding and extends the record of observed trends in temperature, precipitation, sea level, ice mass, and many other variables recorded by a variety of measuring systems and analyzed by independent research groups from around the world. It is notable that as these data records have grown longer and climate models have become more comprehensive, earlier predictions have largely been confirmed. The only real surprises have been that some changes, such as sea level rise and Arctic sea ice decline, have outpaced earlier predictions.[5]

6.2 Culpable Ignorance

The uncertainties I mentioned above do not undermine the reality of climate change, our understanding of its causes, or the statistical accuracy of some of its predictions. But because it's hard to point a finger at any particular hurricane, drought, or damage to a fragile ecosystem and say with certainty, "This is a result of climate change," and because of the spatial and temporal dispersion of the effects of increased GHG emissions, it remains difficult for many people to comprehend the important cause and effect relationships involved. The uncertainties and the difficulty in pointing to specific events that would make the issue salient to the broader public open a door for political pressure from those who would profit most from inaction in the face of climate change, or from promoting a "business-as-usual"

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[4] Intergovernmental Panel on Climate Change, *Fifth Assessment Report*, http://www.ipcc.ch/report/ar5/

[5] U.S. Global Research Program, "The National Climate Assessment," 2014, http://nca2014.globalchange.gov/

path that would continue to increase both the amount and rate of GHG emissions each year.[6] These uncertainties and irreducibly statistical facts pave the way for those who would continue to spread doubt about climate change to be politically effective, even when some of their claims are demonstrably false. But effectiveness is not a moral excuse for denial. If we assume that the consensus views of scientists are more or less correct, there still remains much to debate about what we ought to do and why. But to refuse to take seriously what the experts are telling us about a problem of such magnitude to which we all contribute is to be dishonest, or at least culpably ignorant. This is as irrational and irresponsible as denying that life evolves. The fact that some people will forever claim that the earth is flat, or deny that smoking harms human health, is not a morally excusable reason to believe them or to hold them blameless for sowing unreasonable doubts. One needs to examine the evidence to determine what is credible, and we should hold each other responsible both for denying uncomfortable facts in the face of convincing evidence to the contrary and for producing and promulgating unsound scientific claims in an effort to confuse people and obfuscate the facts in order to increase profits or gain attention. Given the importance of the issue, it seems to me not unfair to judge the actions of some influential climate deniers as morally evil.

It is important also to understand that climate change *itself*, and not just our response to it, is a moral issue. This claim requires at least a brief further comment. The worst harms caused by global warming will consist primarily in “natural disasters,” such as sea level rise, increases in severe floods, hurricanes, droughts, and damage to ecosystems resulting from increased species extinction and the inability of ecosystems to adapt to sudden changes. Like earthquakes (which are not affected by climate change), these natural disasters are traditionally reckoned as tragic but not *morally* significant events. Moral issues are involved in how we *respond* to an earthquake or to the risk of an earthquake, but the event itself is not a moral issue, because it is out of our control. So-called “acts of God” are not our responsibility and thus escape moral judgment. As we now know, however, climate change is not strictly an act of God but is largely caused by human activity. A recent joint report of the U.S. National Academy of Sciences and the British Royal Society explains that climate models that simulate how natural factors alone influence the climate system “yield little warming, or even a slight cooling, over the twentieth century. Only when models factor in human influences on the composition of the atmosphere are the resulting temperature changes consistent with observed

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[6] According to data compiled by the Center for Responsive Politics, oil and gas interests contributed more than $70 million in the U.S. to federal candidates in the 2012 election, and they have spent more than $100 million each year since 2008 in lobbying expenses. The leading five recipients of campaign contributions in the current Congress include both the Speaker of the House of Representatives and majority leader of the Senate. Sen. James Inhofe (R-Oklahoma), author of *The Greatest Hoax: How the Global Warming Conspiracy Threatens Your Future*, recently became the ranking majority member and chair of the Senate’s Environment and Public Works Committee. After being sworn into office on Jan. 6, 2015, he released a statement announcing, as one of his primary goals, to “rein in EPA’s job-killing regulations.”

changes."[7] Human fingerprints are now on the causes of "natural disasters" that are created or made worse by climate change. This creates some new issues for moral philosophy, but it also means that we need a new way to conceive of natural disasters that more accurately represents our responsibility for their occurrence.

How serious is the problem? Although the precise effects of global warming are uncertain and fixating on any number is somewhat arbitrary, scientists have focused on an increase of 2 °C (3.6 °F), as a threshold temperature. They believe that if we can limit global warming to a rise in temperature of that amount above the average pre-industrial age temperature of the Earth, we should be able effectively to mitigate the effects without precipitating a global economic crisis. But, they warn, if we are to limit global warming by this amount, we need to begin very quickly to reduce overall emissions, because our emissions continue to accumulate and remain in the atmosphere for decades and centuries. If we fail to act soon, that is, if we continue on the "business-as-usual" path, scientists worry that temperatures will rise by more than this amount before the end of this century. That is still a long way off, but of course the effects are already beginning to be felt and will increase before hitting that threshold.

What happens if we fail to limit our emissions in a way that keeps us under the 2 °C threshold? The Fifth IPCC Assessment Report states that the prevailing view among scientists is that "exceeding that level could produce drastic effects, such as the collapse of ice sheets, a rapid rise in sea levels, difficulty growing enough food, huge die-offs of forests, and mass extinctions of plant and animal species."[8] The report warns that only with an intense push over the next 15 years can we manage to keep planetary warming to a tolerable level below that threshold. Ottmar Edenhofer, co-chair of the committee that wrote the volume of the IPCC Report on the impacts of climate change, stated in April 2014, "We cannot afford to lose another decade. If we lose another decade, it becomes extremely costly to achieve climate stabilization."[9]

6.3 International Responses

Anthropogenic climate change is a species-induced problem. How have we responded so far? Publication of the IPCC First Assessment Report in 1990 called attention to the human causes of climate change and reported the warming effects over the previous century. This information made a sufficient impact to lead many nations around the world to convene the Rio Earth Summit in 1992, and the Rio Summit resulted in an international agreement, the United Nations Framework

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[7] *Climate Change: Evidence and Causes*, op. cit., p. 5.

[8] Justin Gillis, "Climate Efforts Falling Short, U.N. Panel Says," *The New York Times*, April 14, 2014.

[9] Justin Gillis, Ibid.

Convention on Climate Change. It called for "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system," and it endorsed "common but differentiated responsibilities," that committed richer nations to take the lead in cutting emissions while developing nations would continue in the present to pursue their own policies and take significant action to curb their emissions in the future. Many of the rich countries of the world, including the United States, announced that they would voluntarily reduce and stabilize their emissions at 1990 levels by 2000.[10]

This agreement turned out to be ineffective. U.S. emissions, for example, increased by 10 % during that decade. In 1997, amid growing evidence and understanding of the effects of anthropogenic climate change, the nations of the world met again and agreed to the Kyoto Protocol, which required wealthy nations to reduce GHG emissions to roughly 5 % below 1990 levels between 2008 and 2012. This was thought at the time to be a historically important agreement, but after initially agreeing to the Protocol, the United States Congress refused to ratify it, and the newly elected administration of President George W. Bush withdrew U.S. support and declared the Protocol "dead." The next major summit, in Copenhagen in 2009, was the most recent international effort to implement the Rio document, but this summit was a complete failure that resulted only in drafting yet another accord that ended up being officially "noted" but neither "welcomed" nor endorsed.

The next international summit to discuss climate change is scheduled for December 2015 in Paris. What should we expect from that meeting? The history of global inaction so far, together with the extremely partisan political reactions to climate change proposals in the United States, suggest that we should not be very optimistic. But the situation is far from hopeless. In November, 2014, the U.S. and China entered into a bilateral agreement that would require the U.S. to reduce its emissions to at least 26 % below 2005 levels by 2025, and China agreed to try to cap its CO_2 emissions by 2030, at which time it would also attempt to produce at least 20 % of its electricity with non-fossil fuel sources. What results from this agreement remains to be seen, but many observers regard it as a hopeful sign that the two largest emitters of GHGs have agreed to take significant action to reduce their emissions.

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[10] For a good discussion of the history and failures of efforts to reach and implement international agreements to control climate change, see Stephen Gardiner, *A Perfect Moral Storm The Ethical Tragedy of Climate Change*, Oxford University Press, 2011.

6.4 Duties of Justice and Duties of Goodness

Against this background, I turn now to explore how a better understanding of the ethical problem helps to explain the history of international inaction and motivates a suggestion about how a different strategy, which includes unilateral actions and piecemeal bilateral agreements, might be more effective at bringing meaningful actions to control GHG emissions than international summits. This requires looking beyond arguments about rights, duties, and justice, and paying close attention to some other aspects of ethics and moral psychology. Because climate change is a global problem, we tend to fixate on finding international solutions, and the results so far have been discouraging. Perhaps we can discover a more promising prospect if we look at the problem from the bottom up and see what concerns might be most likely to motivate people and nations to change behavior.

The ethical challenge of climate change, as many writers have noticed, is due to the problem's unique spatial and temporal dispersion of causes and effects. Literally billions of agents around the world emit GHGs. These emissions enter the atmosphere and become unidentifiably mingled with the emissions of every other individual and nation, where they accumulate and remain for decades and centuries as they gradually but steadily change the atmosphere. The harmful effects, which can occur decades or centuries in the future, are also distributed around the world. Nothing any individual does, and to only a slightly lesser extent no action that any nation by itself is likely to take, can make a noticeable difference. How can we think meaningfully and effectively about moral responsibilities in this situation?

In a recent book on the ethics of climate change, John Broome distinguishes two kinds of moral duties that are familiar in philosophy: duties of goodness and duties of justice.[11] Individuals and states typically have duties of both kinds. As individuals, we have duties of justice to other individuals. For example, we ought to keep our promises; we ought not needlessly harm other people and must compensate them when we do; and we ought to treat other people fairly. We also have duties of goodness, which require us to respond to suffering, come to the aid of others in need when we can, clean up after ourselves, and avoid making the world worse in various ways. Governments also have duties of justice and duties of goodness. For example, governments have strong duties of goodness to promote the wellbeing of their citizens. They must build roads, maintain a country's infrastructure and financial system, provide schools and education, and more. And governments have duties of justice that include treating citizens fairly, protecting individual rights, keeping international agreements and responding to human rights abuses around the world. Individuals are also citizens, of course, so individuals have a further duty to support and promote the morally required actions of their governments.

With respect to climate change, however, Broome surprisingly argues that moral duties divide in an unusual way. He claims that individuals have strong duties of justice but minimal duties of goodness, and governments have minimal duties of

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[11] John Broome, *Climate Matters: Ethics in a Warming World* (Norton 2012).

justice but strong duties of goodness. I believe that Broome has things almost exactly the wrong way around, but to see why, we should briefly examine his arguments.

Broome claims that individuals have strong duties of justice with respect to climate change because we knowingly and voluntarily emit GHGs that will harm other individuals. Thus, we each have a duty of justice either to stop causing this harm or else to compensate our victims. Because of the temporal dispersion of cause and effect of GHG emissions, many of the victims of our actions have not yet even been born, and because of the spatial dispersion of cause and effect, we will never be able to identify the individuals that are harmed by our individual actions. So individual compensation for this injustice is impossible. Broome thus concludes that individual duties of justice require each of us to reduce our net GHG emissions to zero. He explains further, however, that we do not have to undergo radical changes in the way we live in order to achieve this result. We can make modest changes in our behavior to reduce some of our emissions, and we can offset the remaining emissions that we produce. In other situations, of course, we could not eliminate an injustice simply by producing a comparable "offsetting" benefit. I do not remove the injustice of borrowing your car without permission, for example, by leaving some good books or even some money on your doorstep. But the fact that our individual GHG emissions are indistinguishable from other emissions means that reducing emissions somewhere else, in order to achieve a net zero outcome, is as good as reducing my own emissions and will allow me to fulfill my individual duty of justice. The problem with this view, as I see it, is that Broome does not defend a moral theory that implies that harms that are so small to any individual, which cannot be traced to any individual and which result from normal activities in the societies in which we live could plausibly count as matters of injustice. Our normal activities create all sorts of minor nuisances for other individuals, but unless they pass some threshold of seriousness, we rarely think that they are unjust.

Broome also argues that individuals do not have strong duties of goodness with respect to climate change. We have duties not to waste resources, so we ought not to leave the lights on in empty rooms or fail to turn the heat down in an empty apartment, but there is little that any individual can do to lower, even in the slightest, the risks or the consequences of climate change. And if an individual lives in a state that has implemented a cap-and-trade system for reducing its GHG emissions, then any individual reductions are likely to be completely without effect, because they will be offset by increases elsewhere. That is how a cap-and-trade system is supposed to work.

For this reason, according to Broome, duties of goodness in this area—that is, duties to reduce the risks and the harms of climate change worldwide—rest with governments and global actions. Governments also have the primary responsibility to develop technologies that can mitigate the harms and help societies adapt to the future unavoidable harms that we have caused. But for various philosophical reasons, Broome does not think it is correct to see these duties as requirements of justice.

Other philosophers have addressed the ethics of climate change in other ways, usually by trying to apply the kinds of moral reasoning that are familiar and well developed in normal contexts to this unique problem. Although many of these arguments are conceptually provocative as philosophical exercises, I do not think they provide the kinds of reasons that are likely to convince and to motivate most individuals, firms, or states to take strong and effective actions in response to climate change.

My point is not that sound moral arguments alone may fail to lead some actors to put aside selfish, short-term interests for the sake of the good of mankind and the planet. That is a depressingly familiar fact about our world and our species. Rather, I find that many of the standard moral arguments do not seem to be an effective response to the unique nature of the harms of climate change. In order to see why this is so, we must take a closer look at the structure of the ethical problem and the interaction of the spatial and temporal dimensions.

6.5 The Structure of the Spatial Moral Problem

The spatial dispersion of the causes and effects of climate change implies that this is a collective action problem on a global scale. And the temporal lag between cause and effect means that it is a classic example of an asymmetrical intergenerational moral problem. As a practical moral problem, climate change thus has unprecedented spatial and temporal elements.[12] First, the spatial element: the CO_2 any agent emits enters the atmosphere and becomes unidentifiably mingled with the emissions of every other individual and nation on Earth. The effects of these emissions are then distributed globally. It is impossible to allocate responsibility for specific harms to any individual actors. Second, the temporal element: there is a foreseeable delay between cause and effect that is virtually unprecedented in our moral life. Our emissions today become part of a pipeline, so to speak, that changes the concentration of greenhouse gases, generates feedbacks that can exacerbate the problems, and then produces effects that will not be fully realized for decades or for more than a century. This is the paradigm of an intergenerational moral issue. What I want to argue now is that these two structural features of the problem not only help to explain the reason for failure to respond in obvious necessary ways but also have characteristics that motivationally pull us in different directions.

Begin with the spatial element. The problem has the structure of what game theorists call a prisoners' dilemma and, more specifically, the closely related problem known as the tragedy of the commons. These problems involve deep conflicts between what is individually rational and what is collectively good.

In the classic version of the prisoners' dilemma, each prisoner, pursuing his own interests, is rationally motivated to choose a certain option, regardless of what the

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[12] These issues are discussed in detail in Stephen M. Gardiner, op. cit.

other prisoners do. But the collective result of each individual successfully pursuing his best rational strategy is an outcome that is worse for each of them than another outcome they could have chosen. They suffer this result because they act alone rather than acting cooperatively with others, and it is in the interest of each not to cooperate even if the others do cooperate. Hobbes' political philosophy is based on the prisoners' dilemma. In the state of nature, it is in the interest of each individual to keep and to exercise all of his natural rights, whatever other individuals do, but the result is that the life of man is "solitary, poor, nasty, brutish, and short."[13] Hobbes argues that each person thus has a rational obligation to surrender all his rights to a Leviathan, on condition that others similarly surrender their rights. The Leviathan then protects the individuals from their natural fate. Except in situations where there is a strong natural basis of trust or else all the individuals in a situation are motivated by moral ideals that are stronger than their instincts to pursue their own individual interests, the only solution to a prisoners' dilemma is either to change the problem by changing the payoffs, or introduce some enforceable agent like a Leviathan that can compel everyone to do what is better for each of them than the solution they can reach by acting individually.

The tragedy of the commons is a variation of this problem.[14] In the classic example, once the commons has reached its carrying capacity for grazing livestock, any additional animals will lower the value of the entire herd. Each herdsman will gain by adding an animal, because he will capture all the benefits while the costs will be distributed among all the herdsmen. But since all the herdsmen have identical incentives, the result will be overgrazing that will make each of their situations worse. The solution, again, is to change the commons, either by privatizing it or by regulating it, so that each herdsman no longer benefits by adding stock that will exceed the carrying capacity.

The analogous problem with climate change is that each nation benefits more than it suffers from its own addition of greenhouse gases to the atmosphere, at least for now. But the result of all nations adding greenhouse gases is worse for everyone. Although the climate change problem has been compared to both of these classic game theory examples, it more closely resembles the tragedy of the commons than the prisoners' dilemma, because the prisoners' dilemma involves one or a series of binary choices, while the commons problem involves incremental decisions.

There is a further important aspect to the spatial problem that interacts with the temporal dimension. Since the beginning of industrial revolution, the nations that have industrialized and become wealthy have been by far the greatest producers of greenhouse gases. Poorer and developing nations have historically contributed virtually nothing to the buildup of greenhouse gases, and many of these poorer nations continue to have minuscule carbon footprints today. But many of these nations are located in areas that will suffer the earliest and worst consequences of climate change if nothing is done to prevent it, so this seems to many moral

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[13] Thomas Hobbes, *Leviathan*, chap. XIII.

[14] See Garrett Hardin, "The Tragedy of the Commons," *Science* 162 (1968): 1243–1248.

philosophers to be an obvious instance of a great global injustice. Moreover, the most populous nations in the world—India and China—are also striving to become as economically developed as the wealthy nations of Europe and North America, and their path to development mirrors the path taken earlier by the currently wealthy nations, which means that they are dramatically increasing energy production that relies heavily on coal which will vastly increase the build-up of CO_2 in the atmosphere, possibly to the extent of neutralizing any reduction the economically developed countries could practically take. The global problem cannot be solved without these nations curtailing their emissions, but it may appear that the wealthy nations that are advocating climate change agreements are pressuring these developing nations not to take the course toward modernization and growth that wealthy nations have already successfully taken. And this, of course, raises a further issue of global justice.

This situation partially explains why no effective international agreement to limit global emissions has been reached. No individual nation seems able to be motivated by considerations of justice to implement adequate policies in the absence of an assurance that other nations will implement similar policies. Rich nations have been reluctant to acknowledge that any effective global measures means that not only do they have to drastically reduce their own emissions, but they will have to both help mitigate the effects of climate change in the poor and most vulnerable nations and also subsidize the search for climate-friendly ways for developing nations to continue to develop.

Recent bickering over the executive summary of the latest IPCC report may thus be a harbinger of a continuing stalemate of nations concerned primarily to protect their own interests from reaching a reasonable global agreement on climate change policies. This stalemate is an instance of a prisoners' dilemma or a commons problem. We are stuck in a Hobbesian state of nature. It is not that individual actors (in this case primarily nations) are morally corrupt. Rather, the problem is that in the absence of a mechanism of international enforcement, the natural pull of individual and national self-interest continues to triumph over the willingness to accept sacrifices for the sake of the greater global good. And, as in the prisoners' dilemma or the tragedy of the commons, the foreseeable result is a worse outcome for everyone.

Viewing the problem either as a matter of global justice or a conflict between individual and collective rationality suggests that the solution is to be found in something like a Leviathan, a world government, or an agency that could allocate responsibilities and enforce agreements that would lead individual actors to curtail narrow individual interests for the sake of the general good. In other words, we need something that can make us all see the problem in its global terms and see ourselves as global actors, citizens of the Earth, not just agents on our own or members of our local tribes and nations. Framed the right way, this can seem like a noble calling and, who knows, it may even garner some political support. But recent history suggests otherwise; we shouldn't hold our breath.

Against this backdrop, we can begin understand why the bilateral agreement recently reached between the U.S. and China is a major achievement and a possible game-changer. Granted, this is an agreement reached only by two heads of government, but if it can gain more widespread support in both countries, it will not only reduce emissions from the two largest contributors but also suggest a new strategy for attacking the problem. It might be easier for developed nations that are strongly motivated for their own local reasons, which I will describe presently, to strike individual bilateral accords with developing and underdeveloped nations that will make the reductions of the wealthier nations more effective in changing the future that they will inherit. So far, of course, this is little more than a hope that a new strategy might lead to a breakthrough that has eluded the efforts to implement effective international agreements. Whether a strategy along these lines has any chance of success depends on how the problem is viewed locally. And here, I want to suggest, we should look not at the global issue but the temporal one.

6.6 The Asymmetry of the Temporal Problem

The temporal problem had been described as an instance of the tyranny of the present over the future.[15] Intergenerational ethics is marked by a lack of reciprocity. Why should we care about the future? What have future generations done for us? Past generations caused much of the problem, which we inherited. We can either accept the costs necessary to begin solving it, or we can refuse to accept those costs and pass a bigger problem on to succeeding generations. They will, of course have the same reason to "pass the buck" that we now have.

Can we be motivated to restrain our short-term interests for the sake of our descendants? As it happens, I think it is clear that a motivation to care about one's descendants is widespread and strong. Parents willingly sacrifice for their children, their grandchildren, and further descendants. Tribes, nations, and cultures commonly see society, in Edmund Burke's words, as "a partnership not only between those who are living, but between those who are living, those who are dead and those who are to be born."[16] Most individuals are not naturally purely selfish and egoistic. We see ourselves as links in a chain that connects past, present, and future. We inherited our culture, our values, and a great deal of knowledge from our ancestors. We modify and add to them, and we pass them to our descendants in the hope that they will respect, value, and continue to improve what matters to us. Thus, we are concerned to protect and preserve historical and cultural artifacts for future generations, and we care that the projects and aspirations that give meaning to our lives will make a positive mark on the world that will continue to be felt and will influence human development after we die.

In a recent book that brilliantly explores these issues, Samuel Scheffler argues convincingly that our lives would lose much of their meaning and value if we

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[15] See the discussion in Gardiner, op. cit.

[16] Edmund Burke, *Reflections on the Revolution in France*, 1790.

became aware that human life would end shortly after we died.[17] Although future generations cannot enter into bargains with us, they hold important cards in their hands. These include the willingness to complete the projects that we undertook and value without any expectation that we would finish them or realize their fruits in our lifetime. We continue to carry on research in the hope that future generations will find applications for it to achieve good ends and better their lives. We try carefully to husband the natural resources and social capital that we expect to bequeath to the future, hoping that they will make the best of it. We entrust to them the continuation of our culture, respect for their heritage and our reputations. These are the kinds of values that make life for many of us today worth living, and they have built into them a concern for our descendants' interests.

If a motivation to care about the future is natural and implicitly alive in us, as I am claiming, how can it be made salient enough to make us care enough to accept some sacrifice to our wellbeing now for the sake of the environment that future generations will inherit? As I see the issue, these motivational springs are more local than global. We naturally care more about our own families and perhaps our fellow tribe members or citizens than about the future of humanity in general. Thus, the pressure to see ourselves in global terms, as citizens of the Earth, in order to motivate us to solve the spatial problems of climate change, is at odds with the tendency to see ourselves more locally, as members of families and tribes that generate and preserve local cultures through time and for the future.

Taking the spatial and temporal elements together, the structural problem of climate change ethics is to find a way to frame the issue that makes the global values of justice and the intergenerational values of a concern for posterity simultaneously salient. To the extent that the two frameworks pull in opposite directions, the moral problem supports reasons for pessimism about finding an efficient and effectively motivating solution in the short time that may be available to us.

Climate change also threatens other structural features of our background values that I can only mention. Solving the spatial problem may require us to limit our sovereignty as individuals and nations. And solving the temporal problem may demand some further severe restrictions on democracy. This latter claim is reinforced by reflecting on why Burke also believed that society, as a partnership of past, present, and future generations, may require members of the present generation to act as trustees of the interests of the past and future. He saw this as a reason to give power to a natural aristocracy that could mediate conflicts among generational interests by choosing what is best to conserve and passing it on. Some recent commentators have also suggested that solving the climate change problem may require severely limiting our democratic powers.[18] This may be right. It may

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[17] Samuel Scheffler, *Death & the Afterlife*, Oxford 2013. I have made a similar argument in "A Moral Requirement for Energy Policies," in D. MacLean and P. G. Brown, eds., *Energy and the Future*, Rowman & Allenheld, 1983.

[18] These tensions are provocatively explored in a review of Gardiner, *op. cit*. See Malcolm Bull, "What is the Rational Response?" *London Review of Books*, vol. 34, May 24, 2012.

be that decisions based on simple, direct democratic processes, which today seems to mean legislators relying very heavily on opinion polls, will never succeed in keeping narrow and short term interests sufficiently in check to give voice to deeper values and concerns that most of us share. But direct democracy, in this sense, already signals a failure of the democratic values and principles that are the foundation of most modern states today.

6.7 A Concluding Thought

The recent report of the U.S. National Academy of Science and the Royal Society on climate change concludes by listing the options for responding to the scientific facts.

> Citizens and governments…can change their pattern of energy production and usage in order to limit emissions of greenhouse gases and hence the magnitude of climate changes; they can wait for changes to occur and accept the losses, damage and suffering that arise; they can adapt to actual and expected changes as much as possible; or they can seek as yet unproven ‘geoengineering’ solutions to counteract some of the climate changes that would otherwise occur. Each of these options has risks, attractions and costs, and what is actually done may be a mixture of these different options.[19]

For the reasons I have described, I am not optimistic that we are structurally or motivationally equipped to change our pattern of energy production in ways sufficient to meet our global responsibilities of justice and our intergenerational obligations while the harms of climate change are still primarily in the future. But I am not so pessimistic as to believe that we will simply accept the damage and suffering that will arise. We will adapt to the extent we can, but this may not be sufficient to manage what will become unavoidable if we do not quickly and dramatically change our pattern of energy production. So I believe we will need increasingly to rely heavily on technological fixes or geo-engineering solutions. We will have to learn how to remove CO_2 from the atmosphere and the oceans at the point when the now predictable catastrophes become immanent. Several recent writers have warned of the risks and madness of trying to find geo-engineering solutions to climate change instead of changing our behavior and values today.[20] I believe that we will have to do both and that we have moral reasons to search far and wide to find a solution to this most difficult imaginable moral problem.

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[19] Op. cit., p. B9.

[20] See Clive Hamilton, *Earthmasters: The Dawn of the Age of Climate Engineering*, Yale University Press, 2013.

Chapter 7
Managing Risks to Civil Infrastructure due to Natural Hazards: Communicating Long-Term Risks due to Climate Change

Bruce R. Ellingwood and Ji Yun Lee

Abstract Civil infrastructure facilities play a central role in the well-being of modern society. Lifecycle engineering of such facilities requires consideration of uncertainties in natural hazard occurrence and intensity, and the response of buildings, bridges, transportation networks and lifelines to these hazards. The service periods for certain critical civil infrastructure facilities may extend well beyond the service lives of 50–100 years traditionally adopted for buildings and bridges. The potential effects of global climate change on such facilities, both in terms of frequency and severity of the extreme events from natural hazards, have become a major concern to facility owners and to authorities responsible for managing risk in the public interest. This paper examines issues that must be addressed in life-cycle reliability assessment of civil infrastructure that must remain functional for service periods of several generations.

7.1 Introduction

Civil infrastructure facilities play a central role in the economic, social and political health of modern society. Their safety, integrity and functionality must be maintained at a manageable cost over their service lives through design and periodic maintenance. Hurricanes and tropical cyclones, tornadoes, earthquakes, and floods are paramount among the potentially devastating and costly natural disasters affecting the economic, social and political well-being of modern society

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and impacting civil infrastructure. The potential exists for even larger losses in the future, given that population and infrastructure development in hazard-prone areas of the United States are increasing dramatically; for example, South Florida is projected to have more than 15 million residents by 2050, an increase of nearly 140 % from its 1990 level of 6.3 million, and similar population growth is predicted for California (Hinrichsen 1999). Similar population growth and economic development accompanying urbanization is projected in other potentially hazardous areas of the world. Notwithstanding recent advances in building and construction sciences, the impacts in recent years of major windstorms and earthquakes have highlighted deficiencies in our scientific and engineering knowledge concerning major natural disasters and their socio-economic impact on urban populations, and have provided an impetus for significant advances in engineering practices for design of buildings, bridges, lifelines and other civil infrastructure. Uncertainties in natural hazard occurrence, intensity and the response of buildings, bridges, transportation networks and lifelines are among the largest of the uncertainties that confront engineers and managers of civil infrastructure.

Many spatially distributed civil infrastructure facilities are interdependent, and this interdependence must be considered when assessing their performance during and following the occurrence of extreme hazards, which typically have large geographic footprints (Zimmerman and Restrepo 2006; IRGC 2007). Moreover, in recent years, the potential effects that global climate change might have on both the frequency and severity of the extreme events from natural hazards and their effect on civil infrastructure facilities have become a major concern for decision makers. Finally, service periods for certain civil infrastructure projects may extend well beyond the traditional service lives of 50–100 years that have been traditional for most projects. Such considerations extend the potential consequences of life cycle engineering decisions to future generations, far beyond the customary utilization horizon, budget cycles for public investment, terms of office of elected public officials, or lifetimes of responsible decision-makers. Intergenerational risk-informed decision frameworks that consider facility performance over service periods well in excess of 100 years and extend across multiple generations have received only limited attention (Nishijima et al. 2007; Lee and Ellingwood 2013).

The risk that civil infrastructure will fail to perform as intended or as expected by the owner, occupant, or society as a whole cannot be eliminated entirely and must be managed in the public interest by engineers, code-writers and other regulatory authorities, and public officials. There are significant research challenges facing these individuals and groups, both individually and collectively, in analyzing the risks quantitatively, communicating these risks to decision-makers and to the public at large, and developing appropriate public policies to mitigate risk and enhance community resilience within budgetary constraints.

7.2 Research Challenges

The assessment and management of risk to public infrastructure has numerous components and dimensions: uncertainties in individual hazards (occurrence and intensity) and in individual facility response; correlation among hazards; performance of distributed infrastructure systems exposed to hazards with impacts felt over large areas; interdependence of infrastructure systems (dependence of water on electrical power which, in turn, may depend on water); interdependence of technical, economic, social and governmental systems and institutions; and risk communication—among experts, to decision-makers and to the public at large.

From an engineering viewpoint, risk-informed decision-making for civil infrastructure performance and integrity has three essential ingredients: physics-based models of time-dependent environmental and man-made hazards, material aging and structural deterioration; time-dependent reliability models to capture the uncertainties in facility behavior over its projected service life; and a decision framework that integrates the uncertain time-dependent behavior for purposes of design and condition evaluation and risk management (Ellingwood 2005). Probabilistic modeling of structural demands arising from natural hazards such as snow, wind and earthquake has been customary practice in the civil engineering community for the past three decades, although the probabilistic models have been stationary in nature (implying that "the past is representative of the future"). Likewise, quantitative time-dependent reliability assessment tools have matured in recent years to the point where they can assist in establishing strategies for analyzing risk of aging infrastructure exposed to natural and man-made hazards. Life-cycle cost analysis has become an accepted tool for managing public investments in performance enhancement and risk mitigation (Frangopol and Maute 2003; Petcherdchoo et al. 2008; Kumar and Gardoni 2014). However, these current quantitative risk-informed assessment procedures account only for decision preferences of the current generation. They will require modification to evaluate performance of critical infrastructure facilities over extended time frames, to recommend alternative design and maintenance procedures, and to support sustainable decisions regarding long-term public safety (e.g., Rackwitz et al. 2005; Nishijima et al. 2007).

A number of key issues must be addressed as part of life-cycle engineering, reliability assessment and risk-informed decision-making: How does one measure acceptable performance in reliability terms? How can uncertainties in future demands and structural aging mechanisms be integrated in time-dependent structural reliability analysis to demonstrate compliance with reliability-based performance objectives? How can one deal with the non-stationarity in demands from natural hazards that arise as a consequence of climate change and in changes in structural behavior that arises from aging? How does one deal with life-cycle cost issues—discounting, decision preferences, and social goals—that arise when service periods in which life-cycle analysis has been successfully applied to periods extending over multiple generations? How does one measure costs consistently and distribute benefits from generation to generation in an equitable fashion? How does one communicate risk effectively to project stakeholders, the public, and regulatory authorities? These issues must be addressed to achieve sustainable solutions to many pressing infrastructure problems. The following sections in this paper will touch upon possible answers to these key questions, considering common structural degradation mechanisms and demand models, practical time-dependent reliability analysis tools and methods for assessing life-cycle performance and offering perspectives on risk that are germane to inter-generational equity in civil infrastructure decision-making for the long term.

7.3 Time-Dependent Reliability Assessment

7.3.1 *Measuring Performance in Reliability Terms*

Time-dependent reliability assessment requires stochastic models of both resistance and load. The probability of survival during time interval $(0, t_L)$ is defined by the reliability function, $L(t)$:

$$L(t_L) = P[R(t_1) > S(t_1) \cap \ldots \cap R(t_n) > S(t_n)] \tag{7.1}$$

which can be related to the conditional failure rate or hazard function, $h(t)$:

$$L(t) = \exp\left[-\int h(\xi)d\xi\right] \tag{7.2}$$

where $R(t)$ is the resistance at time t and $S(t)$ is the dimensionally consistent structural action (moment, shear, etc.) from the applied load at time t. As part of the development of first-generation probability-based codes three decades ago, extensive reliability assessments were conducted to determine measures of the reliability of acceptable performance (Ellingwood 1994). These early methods presumed that the resistance and loads could be characterized as random variables. Methods for determining the survival or failure probabilities of structural components or systems as functions (or intervals) of time from stochastic process models of deterioration, residual strength and service and environmental loads also are reasonably mature (Mori and Ellingwood 1993). However, such analyses generally have treated the service and environmental demands as stationary in nature—here, the mean rate of load occurrences are constant and the load intensities are identically distributed (and often statistically independent). The stationary assumption is not reasonable when the time-dependent reliability analysis involves demands that are the result of evolving geophysical or climatological influences due to global climate change, causing the frequency and intensity of the events to increase in time. Only rudimentary tools to perform such an analysis are available (Bjarnadottir et al. 2011) at the present time.

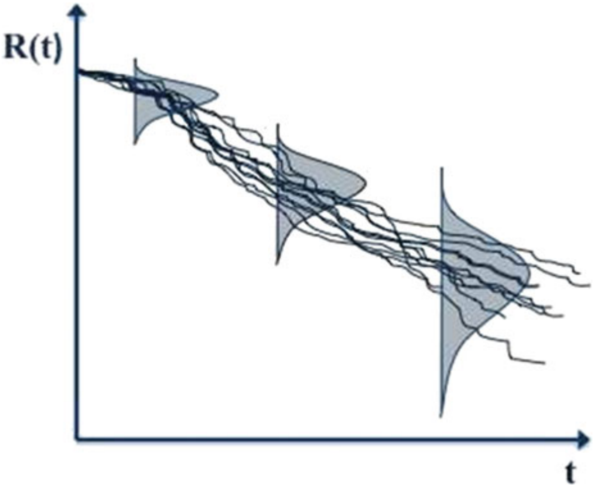

Fig. 7.1 Stochastic models of aging

7.3.2 Physics-Based Structural Deterioration Models

Changes in material properties due to aggressive service or environmental conditions may lead to deterioration in the engineering properties of structural components and systems over time. Aging mechanisms that cause deterioration of concrete structures may be produced by chemical or physical attack on either the cement-paste matrix or aggregates. Degradation in strength of steel shapes or steel reinforcement in concrete can occur as a result of corrosion, elevated temperature or fatigue. In addition to the above, pre-stressing or post-tensioning systems are susceptible to loss of pre-stressing force due to stress relaxation.

Much of the literature on structural deterioration mechanisms has been developed from small specimens tested under laboratory conditions. These tests have been conducted in different environments and at different scales that would be typical for civil infrastructure (Bentz et al. 1996; Liu and Weyers 1998; Naus et al. 1999), and the relevance of these data to structural engineers seeking to manage risks in aging civil infrastructure is questionable. Most models of structural deterioration that have been used in time-dependent reliability analysis of aging infrastructure are relatively simple because supporting data for measuring deterioration of structures *in situ* are limited. One such stochastic model of deterioration is schematically shown in Fig. 7.1 (Ellingwood 2005). Such models are difficult to generalize to environments not reflected in the database. *In situ*, service conditions are difficult to reproduce in laboratory tests and scaling to prototype conditions raises additional uncertainty that is difficult to model. The uncertainty in deterioration is even less well-understood, but will have to be quantified to assess risks over time frames of interest in public decision-making.

7.3.3 Structural Load Modeling Under Climate Change: Nonstationary Hurricane Simulation Model

As noted previously, most statistical analyses of climatological data (wind speeds, snow loads, temperatures, and precipitation) have been based on the assumption that the extremes of interest from a stationary sequence of identically distributed and statistically independent random variables. When the demands placed on the structure are the result of climatological parameters that reflect evolving geophysical or climatological influences due to global climate change and cause the frequency and intensity of the events to increase in time, the assumption of stationarity in time-dependent reliability analysis is not tenable. The American Society of Civil Engineers has formed a Committee on Adaptation to Climate Change to consider the potential impact of climate change on civil infrastructure design. This committee's work is very much in the formative stage.

One of the most significant impacts of climate change on structural engineering practices is found in the hurricane wind speeds that determine the wind forces used to design buildings and other structures (ASCE 7-10). Wind forces on structural systems are proportional to the square of the wind speeds for buildings in which aeroelastic effects are insignificant.[1] The current design-basis wind speed (at a return period of 700 years for Risk Category II buildings) is 170 mph; if this wind speed were to increase to 185 mph over the next century due to climate change, the design forces would increase by 18 % and the cost of the structural system of a typical building would increase by a similar amount.

In Sect. 7.4, we illustrate the potential impact of nonstationarity in hurricane occurrence and intensity on the design wind speed. To simulate these non-stationarities, we begin by utilizing a track modeling approach originally developed by Vickery et al. (2009), which is the basis for the wind speed maps in the United States (ASCE 2010), but modify it to account for nonstationarity in occurrence and intensity. Figure 7.2 illustrates the occurrence of storms in the Atlantic Basin obtained from the HURDAT2 database (HRD/NOAA 2014), clearly revealing that the annual frequency of historical storms over the Atlantic Basin has increased since 1851. The number of storms to be simulated in any year is sampled from a negative binomial distribution with increasing mean and standard deviation determined from this historical database. A link between sea surface temperature (SST) and hurricane power dissipation (related to hurricane wind speed) recently has been noted (Emanuel et al. 2006), and since the hurricane central pressure is a function of previous pressures as well as the SST, increases in SST as a result of climate change will affect the intensity of storms in the simulation model. The SST at the storm center is obtained from the National Oceanographic and Atmospheric Administration's extended reconstructed model SST V3b, which provides global

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[1] If aeroelastic effects are significant, as they may be for very slender tall buildings, stacks and long-span cable-stayed or suspension bridges, the wind force is proportional to a power of the wind speed higher than two.

Fig. 7.2 Annual number of storm in the Atlantic Basin

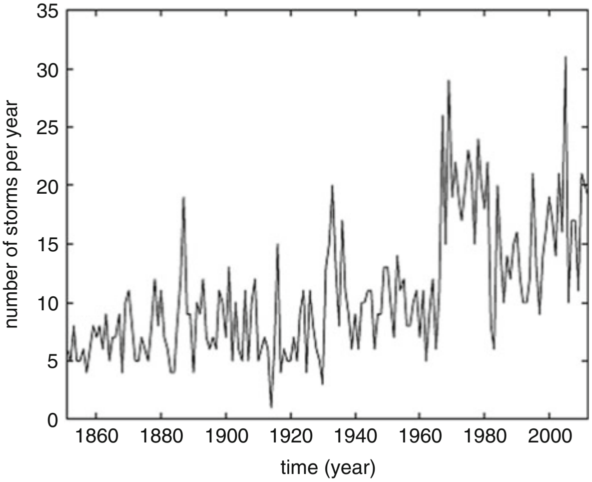
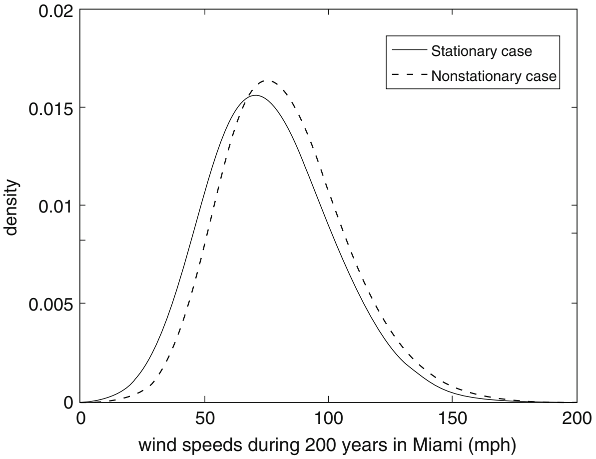


Fig. 7.3 PDFs of wind speeds in Miami over a 200-year service period: Comparison of stationary and nonstationary models of hurricane occurrence and intensity



monthly SSTs from 1854 to the present on a 2° × 2° global grid. Future SSTs on each grid then are estimated from a grid-based auto-regressive integrated moving average (ARIMA) model.

Figure 7.3 illustrates the probability density functions (PDF) for wind speeds over a 200-year service life in Miami, FL (Lee and Ellingwood 2014), showing clearly the difference between wind speeds obtained from stationary (or existing) hurricane simulation models and from the nonstationary hurricane model. Thus, nonstationary hurricane wind speeds with time should be carefully integrated in a time-dependent reliability assessment to achieve more reliable forecasts of facility behavior, especially for extended service periods.

7.4 Intergenerational Risk-Informed Decision Framework

7.4.1 Consequence-Based Decision Models

In current risk-informed decision-making, performance goals generally are expressed in terms of probabilities, expected losses measured in monetary or human terms, or a combination of these metrics, which is generally defined as risk. There is a growing awareness, prompted by recent experience following natural disasters and the new paradigm of performance-based engineering (PBE), that, in addition to public safety assurance, the likelihood of business interruptions, social disruptions, and unacceptable economic losses also must be minimized in certain situations. Accordingly, during the past several decades, different types of decision models have been developed (Rosenblueth 1976; Wen and Kang 2001; Goda and Hong 2008; Cha and Ellingwood 2012). The design intensity and in-service maintenance to maintain safety and serviceability of the facility over its service life should be based on a systematic approach that reflects both aleatory and epistemic uncertainties in both demand on and capacity of civil infrastructure. In order to manage the large uncertainties associated with natural hazards, deterioration processes and facility responses, life-cycle cost analysis and risk assessment have been used to provide quantitative evidence to support design and maintenance decisions (Ellingwood and Wen 2005).

The most mature decision model is based on minimum expected life-cycle cost, which leads to an optimal choice that has a minimum life-cycle cost, while satisfying the constraints on the acceptable level of structural lifetime reliability in service. Considering the time-dependent nature of structural demands and capacity, the cost is a function of time, t (Wen and Kang 2001):

$$E[C(T,X)] = C_0(X) + E\left[\sum_{i=1}^{N(t)} \sum_{j=1}^{k} C_j e^{-rt_i} P_{ij}(X,t_i)\right] \tag{7.3}$$

in which T = the service life of a new structure or the remaining life of an existing structure; X = vector of design variables, e.g., design loads and resistance; C_0 = construction cost for a new or retrofitted structure; $N(t)$ = total number of extreme events in t; k = total number of damage states; C_j = cost in present value of consequence of the jth limit state at $t = t_i$; r = discount rate per year; and P_{ij} = probability of jth limit states being exceeded given the ith occurrence of one or multiple hazard.

Figure 7.4 shows the optimal design intensity obtained from Eq. (7.3) for two cases. In the first, the optimal design intensities, X, are obtained from Eq. (7.3) for the simple case when only one stochastic load and one limit state are considered (solid line) under several restrictive assumptions: the intensities of load variables are assumed to be a sequence of independent and identically distributed random variables; the occurrences of discrete load events in time is modeled as a Poisson

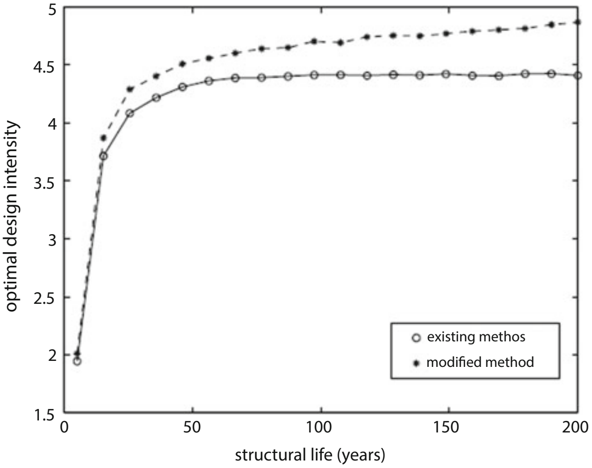


Fig. 7.4 Comparison of optimal design intensities as a function of design life obtained from two different discounting methods

process with stationary increments; and the annual discount rate (4 %) is constant over time. Note that most previous applications of life-cycle cost analysis have focused on decisions for time frames of 50–75 years. The solid line in Fig. 7.4 shows that the optimal design intensity becomes essentially constant beyond 50 years of structural life, implying that the optimal decision is independent of time as service life increases. This result is a consequence of the assumption that two intergenerational elements—discount rate and the probability of failure—are independent of time. Since this decision stance unfairly diminishes the importance of decision consequences to future generations, existing decision frameworks must be modified to allocate costs and benefits equitably between the current and future generations.

7.4.2 Discounting for Intergenerational Risk Sharing

Appraisals of investments in civil infrastructure, as well as government policies, projects, and programs, involve trade-offs between the more immediate costs and the longer-term benefits in the future. The technique used to compare costs and benefits that occur at different points in time is crucial in such decisions; discounting is the accepted method for describing the value in present terms of future outcomes (measured in terms of damages, costs, benefits, or utility values). The discount factor, $D(t)$, gives the value of an increment in consumption at a time in the future relative to the present (or at any other point in time), and is used to convert future cost and benefits into their present equivalents. The discount rate, $r(t)$, is the annual rate of decline of the discount factor and gives the rate at which future value is discounted. In discrete and continuous time domains, the discount

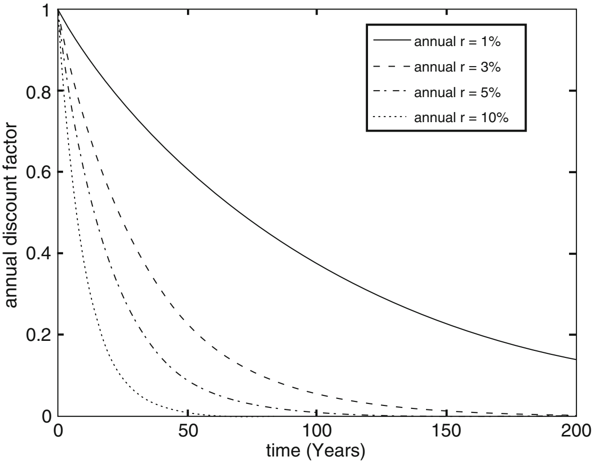


Fig. 7.5 Discount factors corresponding to different annual discount rates

factor can be related to the discount rate shown in Eqs. (7.4a) and (7.4b), respectively (Hepburn 2007):

$$D(t) = \frac{1}{[1 + r(t)]^t} \tag{7.4a}$$

$$D(t) = \exp\left[-\int_0^t r(\tau)d\tau\right] \tag{7.4b}$$

A constant positive discount rate implies that the discount factor declines exponentially, $D(t) = \exp(-rt)$, valuing an increment in future consumption less than an increment in present consumption.

The evaluation of alternative strategies and investments is extremely sensitive to the discount rate. Moreover, the potential influence of discount rate on the long-term assessment is greater, because even small changes in the discount rate have a significant impact on the result of decision-making where discounted benefits and costs continue to accrue over centuries. Figure 7.5 shows discount factors corresponding to the range of 1–10 % annual discount rate. A higher discount rate implies that we place a lower value on future gain or loss than on the same gain or loss occurring now. For example, a dollar of 100 years from now at 1 % discount rate would be valued at 0.37 dollar today, while it would hardly be considered in present decision (valued at 0.0001 dollar today) when employing 10 % discount rate. Exponential discounting with a constant discount rate may be sensible over the short to medium term. For longer time frames, however, it appears to be inconsistent with intergenerational equity and sustainable development (Weitzman 1998; Gollier 2002), diminishing the importance of consequences to future generations in decision-making. The use of conventional discounting methods for projects across multiple generations conflicts within our moral intuitions; an intergenerational approach to discounting should explicitly incorporate the perspectives of both the current and future generations.

A high degree of uncertainty about future discount rates exists when outcomes at some distant time in the future are considered, and this uncertainty plays a significant role in discounting practices. Incorporating uncertainty has been proved to reduce the discount rate over time (Weitzman 1998; Gollier 2002). For distant horizons, the uncertainty in future wealth is very large and the discount rate should be very small. In order to reflect such characteristics of declining discount rate to achieve intergenerational equity in risk, we assume simple form of exponentially decreasing discount rate and apply it to the same example above (summarized in Fig. 7.4) using Monte Carlo simulation. The annual discount rate is assumed to exponentially decrease from 0.04 to 0.01 over a period of 200 years with the form of $r(t) = 0.04e\exp(-\alpha t)$ to avoid shifting too much risk to future generations. At the same time, the mean value of the intensities of load events is assumed to increase linearly by 20 % in 200 years and the incidence of the hazards is represented by a nonstationary Poisson process with a 20 % increasing mean rate of occurrence during the design life. Structural capacity is assumed to decrease linearly by 10 % during 200 years. The dashed curve in Fig. 7.4 indicates that the optimal design intensity clearly increases with service life when considering these time-dependent effects over multiple generations.

7.4.3 *Risk-Informed Optimal Design for Hurricane Hazards*

To illustrate the effects of the nonstationarity in hurricane demand and structural capacity on long-term sustainable decision-making, a special moment-resisting steel frame building was considered. The structure is a nine-story office building having a 75 ft by 180 ft floor plan with a height of 119 ft. The same structure has been analyzed by Wen and Kang (2001) using minimum life-cycle cost analysis, but under the more restrictive assumptions that wind intensities are stationary, that the structure does not deteriorate over time, and that the discount rate is constant. Such assumptions might be justified for a relatively short service life. However, since this study considers multi-generational time frames, four different cases of loading and capacity will be illustrated, as summarized in Table 7.1.

The building of interest is assumed to be located in either of two wind hazard-prone sites in the US: Charleston, SC or Miami, FL. The hurricane simulation model described in Sect. 7.3 is used to generate wind speeds at each location. The

Table 7.1 Four cases of structural capacity and loading conditions

	Resistance	Structural load
Case 1	Constant with random initial capacity	Stationary
Case 2	Decreasing with random initial capacity and degradation rate	Stationary
Case 3	Constant with random initial capacity	Nonstationary
Case 4	Decreasing with random initial capacity and degradation rate	Nonstationary

model by Vickery et al. (2009) can be directly used for Cases 1 and 2 to simulate stationary wind speeds, which also correspond to the basic wind speeds in ASCE 7-10, while the modified nonstationary hurricane model (cf Fig. 7.3) must be used for Cases 3 and 4 to consider climate change effects on wind storms over a service period of 200 years. The initial cost and failure costs, including those due to structural damage, loss of contents, relocation cost, economic loss, cost of injury and cost of human fatality provided in Wen and Kang (2001) have been adjusted to 2013 dollars. In this analysis, the optimal design intensity is the base shear, expressed as a function of the yield capacity of the frame and determined based on its minimum expected cost. The optimal design intensities obtained assuming a constant annual discount rate, 0.05, in Miami, are shown in Fig. 7.6 for the four cases in Table 7.1. The optimal design intensity increases when the effect of aging and/or climate change during the building service life is considered mainly because these effects cause the conditional failure rate to increase in time. When the projected service life is 200 years, the increase in the optimal design intensity is approximately 10 % for the particular building studied.

The discount rate is also a key factor in intergenerational risk-informed decision framework, as noted previously. Figure 7.7 shows the optimal design level as a function of service life, with a very simple form of linearly declining discount rate: $r(t) = 0.05 - 0.0002t$. The two intergenerational elements suggested in Sect. 7.4.1—time-dependent reliability and time-varying discount rate—clearly enable a decision framework to consider the preferences of both current and future generations.

As a final observation, it should be noted that some investigators have argued *against* the use of optimization in setting structural safety targets (Proske et al. 2008). Optimization has some ethical implications and the potential to damage trust; the Ford Pinto case revealed how disturbed the public can be about corporate decisions that balance life safety and cost (Schwartz 1990). One simply cannot state, following a disaster, that the decision leading to that disaster was an

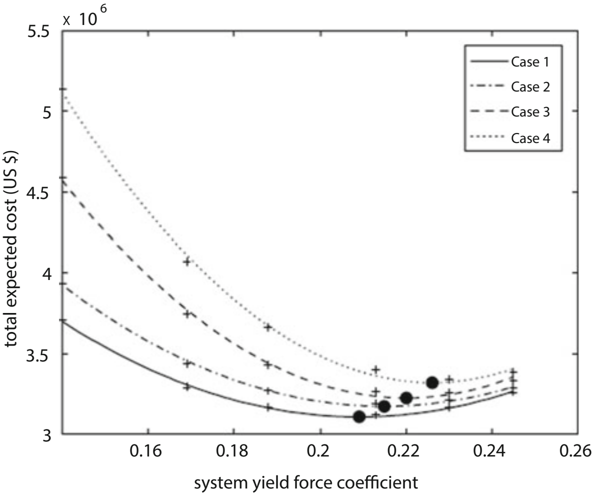


Fig. 7.6 Optimal design intensities of four cases in Miami

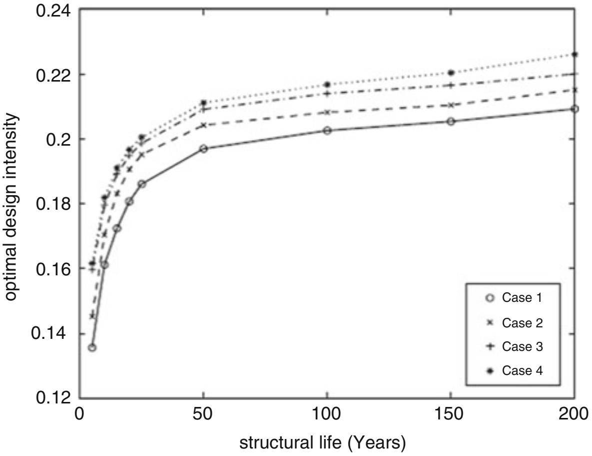


Fig. 7.7 Optimal design intensities of four cases as a function of time in Charleston when considering time-varying discount rate

acceptable one, based on minimum cost and justify that decision solely on that ground. Designing for robustness—achieving an engineered system that is insensitive to perturbations outside the design—is an alternative approach that is only beginning to be explored in the structural reliability community.

7.5 Risk Measurement and Communication

The assessment of loss probabilities or expected losses, once determined, and decisions regarding risk mitigation depend on the decision-maker's view on the acceptability of risk and on whether/how investments in risk reduction should be balanced against available resources. Most individuals are risk-averse while governments and large corporations tend to be more risk-neutral (Slovic 2000). Furthermore, the conventional minimum expected cost approaches presume that the risk can be entirely monetized. There is evidence to indicate that individual decision-makers and many public agencies are risk-averse, meaning that they demand increasing payments for accepting marginally increasing risk (Cha and Ellingwood 2012). Risk aversion is likely to play an increasing role in decisions extending to multiple generations, due to the substantial uncertainties in extrapolating stochastic models of demand and capacity far beyond their previous applications or supporting databases, as well as the uncertainties in decision consequences that might not occur until after decades into the future.

Perhaps the most important step of risk-informed decision-making is communicating the risk to the public and those having authority to implement new policies in such a way that they confront and take ownership of approaches to and investments in risk mitigation. This step is difficult, and the typical engineer or risk analyst seldom is trained to do it effectively. Even educated laymen seldom are risk-informed; the public tends to be highly skeptical of complex technical analyses that it cannot understand. The notion of probability eludes most people. No one knows exactly an annual probability of 10^{-6}/year really means; it only is meaningful when compared to other estimates made using similar assumptions and methodologies. In any event, it turns out that probability is not all that important because public perceptions of risk do not follow the objective definitions of experts in probabilistic risk analysis. The public may take "likelihood" or "the odds" into account, but adds beliefs, recent experiences and prejudices,[2] political perceptions and other factors into the mix. There also is strong evidence that the magnitude of the risk is more important to the public than the probability. In the end, the thought process leading to a judgment on what is *acceptable risk* is "essentially binary" in nature. Furthermore, recent studies (e.g., Murphy and Gardoni 2008; Corotis 2009) have indicated that *acceptance* of risk is based more on its *perception* than on the actual probability of occurrence and that biases in perception, whether or not they are well-founded, shape decisions.

Within the design team, risk communication requires a continuing dialogue among project stakeholders, aimed at facilitating understanding basic issues and enhancing the credibility and acceptance of the results of the risk assessment. Performance objectives and loss metrics must be clearly identified and agreed upon, and uncertainty analysis should be a central part of the decision model. Tradeoffs that occur between investment and risk reduction must be treated candidly, and the entire decision process must be made as transparent as possible. All sources of uncertainty, from the hazard occurrence to the response of the structural system, must be considered, propagated through the risk analysis, and displayed clearly to obtain an accurate picture of the risk.

In the public arena, effective risk education and communication is an ongoing process, which must take individual and public attitudes into account. Trust in institutions and government is at an all-time low. Risk communication should prompt individuals and the public to question their behaviors (Mileti and Fitzpatrick 1991). It should be kept simple—it should deliver an unambiguous message. Experts often don't do a very good job of that. It should give options—presenting the idea of a tradeoff between risk and benefit (or cost) is helpful.

7.6 Closure

Risk assessment and management in an era of climate change and its potential impact on civil infrastructure requires modeling the effects of nonstationarity in demand and the impact of aging and increasing service demands on facilities that may be required to function over substantially longer periods than previously considered (Ellingwood 2005; Frangopol and Maute 2003). Current approaches to civil infrastructure management have given this issue only limited attention. In the area of economics and in life-cycle cost analysis, existing decision-theoretic methods must be modified to remove

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[2] To some, the act of understanding a risk assessment actually legitimizes the threat.

some anomalies that might occur when time horizons are extending to future generations (Nishijima et al. 2007). Perhaps most important is the need to embrace uncertainty and communicate risk at different levels to persuade decision-makers of the need for action, where appropriate. The fact that uncertainty is present often produces anxiety. Even among specialists, risk communication is a barrier: among climate scientists, for example, mitigation is means reducing greenhouse gases; among engineers, mitigating means reducing climate change impacts. The fact that public actions seldom are consistent with the results of a probabilistic risk analysis is an indication that other human factors, such as beliefs, recent experiences and personal preferences and biases play a significant role in risk perception (Corotis 2009). The required public investment will be enormous, and a risk-informed framework involving quantitative scientific tools clearly will be required to establish priorities and strategies. At the same time, the means for conveying the risk mitigation message to a public that, in the past, has not responded to quantitative risk management is perhaps the most significant challenge.

Managing risk is, in the end, an interdisciplinary endeavor, involving the coordinated efforts and activities of engineers, climatologists and geophysicists, computer and information/communication technologists, and social/behavioral/economic scientists. It must include philosophers to determine what is ethical and the legal profession to determine what is possible under our constitutional form of government. Finally, it must involve the public—the stakeholders—who must take ownership of the problems confronting us in order to achieve effective, workable and lasting solutions to civil infrastructure planning, development and maintenance in an era of climate change.

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Chapter 8
Assessing Climate Change Impact on the Joint Wind-Rain Hurricane Hazard for the Northeastern U.S. Coastline

David V. Rosowsky, Lauren Mudd, and Christopher Letchford

Abstract In this chapter, we present results of a study to assess the impact of possible future climate change on the joint hurricane wind and rain hazard along the US eastern coastline. To characterize the hurricane wind hazard, climate change scenarios were coupled with simulation-based hurricane genesis, wind field, and tracking models to examine possible changes in hurricane intensity (maximum wind speed) and hurricane size (radius to maximum winds). A number of different postulated climate change models (IPCC scenarios) were considered. Each scenario suggested changes in sea surface temperature (SST), the driving parameter in most modern hurricane wind field models. The evolution of hurricane genesis frequency and hurricane track behavior were examined, though no temporal trend was apparent in either. A rainfall hazard model was then developed using recorded rainfall data associated with hurricane events and a probabilistic model relating wind and rain was constructed. The pairwise joint distributions of maximum wind speed, spatial extent/storm size, and maximum rainfall rate—under current and future climate scenarios—were developed and compared. Finally, joint multivariate (wind speed intensity, spatial extent/storm size, rainfall rate) distributions were constructed to describe the joint wind-rain hurricane hazard including consideration of projected climate change impacts. Implications for current and future design (code provisions) are discussed.

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8.1 Introduction: Setting the Stage

Hurricanes cause extreme weather and severe damage along impact zones, such as the US east coast, putting major urban population centers at risk. In 2012, US landfalling hurricanes accounted for 143 of the 284 US fatalities caused by natural disasters and over $52 billion in losses (Rosenthal et al. 2013). The severity of hurricane hazards has led to many studies seeking to improve forecasting, warning, and evacuation. However, as meso-scale meteorological events hurricanes are affected by climate change (Emanuel 1987, 2008; Bender et al. 2010), the impact of which has received little attention to date. In order to continue to ensure the safety of our built environment in the future, current design codes and standards must be adapted to account for future climate change impacts on hurricane hazards (wind, surge, and flood). In this work, we make use of similar probabilistic simulation procedures used to create the wind speed maps contained in the US design standard ASCE 7 (ASCE 1993, 2010), and findings can inform updates in coastal design wind speeds for future editions.

In recent years, we have seen the first studies to examine the effect of climate change scenarios on wind, storm surge and flooding. Nishijima et al. (2012) conducted an impact assessment of climate change on the Northwest Pacific typhoon wind risk, focusing on potential damages to residential buildings in Japan. In their work, typhoons were simulated using the Atmospheric General Circulation Model (AGCM) under the 2005 and future climate scenarios. Similar procedures were adopted herein; however, the atmospheric model, the projected scenarios and hurricane models are different, as explained in the following sections. Irish (2008) examined the influence of climate change on hurricane flooding for Corpus Christi, TX and Lin et al. (2012) investigated the influence of climate change on hurricane-induced storm surge for New York, NY. However, the hurricane models used in the two previous studies were deterministic.

The availability of the historical Hurricane Database (HURDAT 2013) maintained by the National Hurricane Center (NHC) has enabled event-based simulation procedures (Vickery et al. 2000a, b) to be developed in the public sector. In Mudd et al. (2014), state-of-the-art hurricane prediction models were used to simulate hurricanes in the year 2100 under IPCC climate change scenario RCP 8.5. A framework developed by Lee and Rosowsky (2007) was then implemented to develop a hurricane wind speed database for the Northeast US coast, including the states of Maryland, Delaware, New Jersey, Pennsylvania, New York, Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire and Maine, under both the 2005 and future climate states. Note that although Vermont and Pennsylvania are not coastal states, they have been affected by hurricanes recently (*e.g.*, Irene in 2011 and Sandy in 2012) and were considered as part of the hurricane-prone US Northeast. Key components of the simulation framework used in Mudd et al. (2014) were the gradient wind-field model (Georgiou 1985) and the tracking and central pressure models (Vickery et al. 2000a, b). The post-landfall decay model proposed by Vickery and Twisdale (1995) was used with site specific decay parameters determined through statistical analyses of historical data. Finally, trends in hurricane genesis frequency and hurricane track were also explored.

The assessment presented herein represents an update to the analysis performed in Mudd et al. (2014). Since the development of the hurricane simulation techniques (Vickery et al. 2000a, b) used in Mudd et al. (2014), significant improvements have been made (*e.g*., Vickery et al. 2009). These improvements consist of an updated statistical model for the determination of the Holland pressure profile parameter and the radius to maximum winds (Vickery and Wadhera 2008), and a new model for hurricane decay after landfall (Vickery 2005). In addition, several major hurricane events have occurred since 2005, which were used as the current scenario in Mudd et al. (2014). The study presented herein makes use of all available historical hurricane data to extend the current scenario to the year 2012. In addition, the most current historical hurricane database (HURDAT 2013) incorporates findings of several re-analysis projects (Landsea et al. 2004a, b, 2008, 2012; Hagen et al. 2012) to correct errors and biases that have previously appeared in the historical data. While storm surge and flooding due to hurricanes also cause damage, only the direct hurricane wind and rain hazards (maximum wind speed, storm size, and rainfall rate) are considered herein. The Northeast US coast was selected as the sample study region; however, the framework can be applied in other hurricane-affected regions as well. Details of the projected future climate change scenarios and the probabilistic hurricane simulation models are described in the following sections.

8.2 Projected Future Climate Change Scenarios: A Look to the Future

The IPCC Fifth Assessment Report (Pachauri 2014) contains several climate change projections in the form of Representative Concentration Pathway (RCP) scenarios. A discussion of the RCP scenarios can be found in Mudd et al. (2014). In this study, only the worst-case projected future climate change scenario, RCP 8.5, was considered. RCP 8.5 is a “high forcing” scenario with 8.5 W/m^2 total radiative forcing in the year 2100. Radiative forcing refers to the difference in radiant energy received by the Earth, and the energy radiated back into space, quantified at the tropopause. Comparatively, the 2005 radiative forcing level, according to IPCC Fourth Assessment Report (IPCC 2007), is 1.6 W/m^2. The radiative forcing estimates are primarily based on the forcing of greenhouse gases. All climate change scenarios from Jan 2005 to Dec 2100, based on the RCP 8.5 pathway projection, were simulated using the Community Earth System Model (CESM 2012). CESM (2012) is a fully-coupled, global climate model that provides state-of-the-art computer simulations of the Earth’s past, present, and future climate states. As the driving parameter of most hurricane models, the monthly average sea surface temperature (SST) values were then extracted from the CESM (2012) simulation

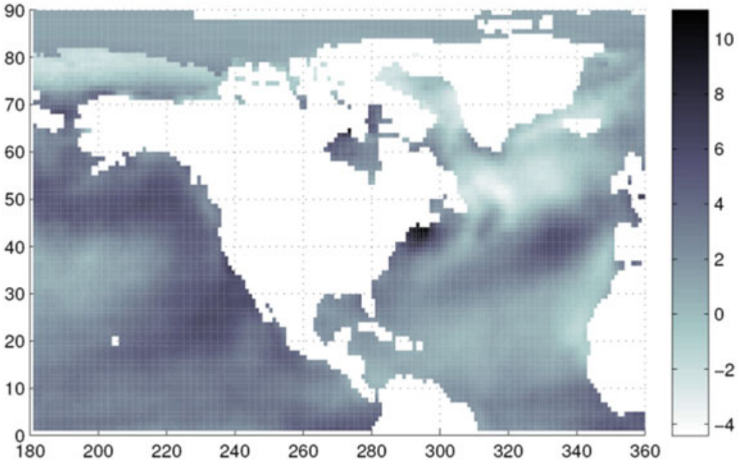


Fig. 8.1 Projected SST change (°C) under climate change scenario RCP 8.5 from August 2012 to August 2100

for use in the hurricane simulation procedures described in the following section. The SST values were originally stored on a displaced-pole grid and were transformed to lie on the regular rectangular 1° × 1° grid. The difference between the current and future SST in August, the most active hurricane month, is shown in Fig. 8.1. This figure shows that the largest SST increases are along the Northeast US/Canadian coast.

8.3 Hurricane Hazard Modeling and Simulation Procedures: The "What-If" Engine

8.3.1 Hurricane Genesis Model

Hurricane events are simulated as Poisson events (*i.e.,* independent events with a fixed average arrival rate). Considering all storms generated in the Atlantic basin and assuming a constant annual hurricane occurrence rate with time, the annual hurricane occurrence rate, λ, for the year 2012 was found to be 8.4 (Lee and Rosowsky 2007). Also considering all storms generated in the Atlantic basin, Mudd et al. (2014) used a least-squares regression to fit a linearly increasing trend to the annual hurricane occurrence rate and found λ for the year 2100 to be 13.9. However, when considering only historical hurricanes that made landfall in the US, no linearly increasing trend in annual hurricane occurrence rates is seen (Mudd et al. 2014), and λ is found to be approximately 2.9 hurricanes per year. The historical data and fitted trends are shown in Fig. 8.2 for all hurricanes occurring in the Atlantic basin and for only hurricanes making landfall in the US.

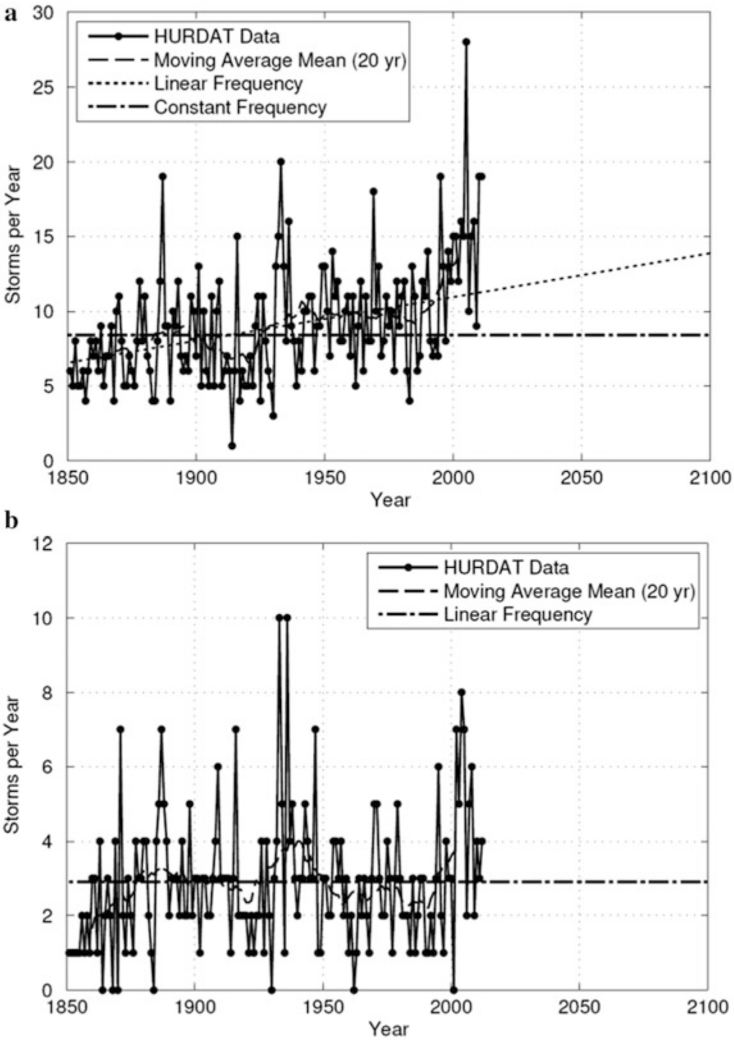


Fig. 8.2 Frequency of (**a**) all hurricanes generated in the Atlantic basin and (**b**) only hurricanes that made landfall in the US

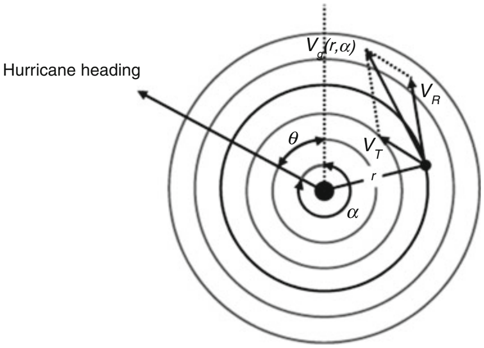
Several recent studies (Mann and Emanuel 2006; Holland and Webster 2007; Mann et al. 2007; Knutson et al. 2008; Landsea et al. 2010; Vecchi and Knutson 2008) have examined the completeness of the HURDAT database and its validity in determining the frequency of occurrence of historical hurricane events. Due to the high variability of the frequency of storms from year to year, as well as physical limitations of past observing and reporting capabilities, no consensus has been reached on the subject. However, in regards to the accuracy of the record of US landfalling hurricanes, there is little debate. Using population data from US census reports and other historical analyses, Landsea et al. (2004a) provided dates for when landfalling hurricane records in specified regions of the US could be deemed accurate. For every geographical region considered, they concluded that the records were accurate after 1900 and that the records along the US Northeast coast may be accurate as far back as 1660. In order to remove a source of uncertainty from the simulations performed herein, this study utilizes an annual hurricane genesis frequency based only upon historical events that made landfall in the US. In addition, limiting the number of historical hurricanes to only those that made landfall in the US results in a lower annual hurricane genesis frequency to be used during simulation (since the number of hurricanes generated that hit the US annually is much less than the total number of hurricanes generated in the Atlantic basin annually.) In generating fewer events during simulation, the required computation time is significantly reduced.

8.3.2 Gradient Wind Field Model

Using information obtained by aircraft reconnaissance observations, the hurricane gradient wind speed can be defined. Aircraft typically record wind speeds at an elevation of 3000 m, which is higher than gradient-level wind speeds, which occur 500–2000 m above the surface. However, it has been shown, by Powell (1990) and Sparks and Huang (1999), that wind speeds measured between 2000 and 3000 m show little variation. Consistent with historical data obtained by aircraft reconnaissance and as shown in a number of other studies (*e.g.*, Rosowsky et al. 1999), well-formed hurricane gradient wind fields can be represented as a vortex with translational movement. Therefore, the gradient wind speed, V_g, can be decomposed into a rotational component, V_R, and a translational component, V_T, as shown in Fig. 8.3.

Since the rotational wind speed is assumed to be symmetrical about the hurricane eye in this study, the rotational component, V_R, can be described as a function of distance from the hurricane eye. The gradient rotational wind speed vortex can

Fig. 8.3 Idealized gradient wind field model



then be determined using this rotational wind speed component. Georgiou's model (Georgiou 1985) describes the rotational vortex shape through Eq. (8.1).

$$V_g^2(r,\alpha) = \frac{r}{\rho} \cdot \frac{\partial P}{\partial r} + V_g(r,\alpha) \cdot (V_T \sin\alpha - f \cdot r) \tag{8.1}$$

where V_g = gradient wind speed, r = distance from hurricane eye, α = angle from hurricane heading direction (counter-clockwise +), ρ = air density, V_T = translational wind speed, f = coriolis parameter and P = surface air pressure. Information needed to statistically characterize these parameters (central pressure, storm track and translational speed) can be obtained from the HURDAT database. The surface air pressure $P(r)$ at a distance r from the hurricane eye is given by Eq. (8.2) (Vickery et al. 2000b):

$$P(r) = P_c + \Delta P \cdot \exp\left[-\left(\frac{R_{\max}}{r}\right)^B\right] \tag{8.2}$$

where P_c = air pressure at the hurricane eye, ΔP = the central pressure deficit (mb) = 1013 – P_c (mb), R_{max} = radius of maximum winds, and B = pressure profile parameter. As an update to Mudd et al. (2014), this study uses models developed by Vickery and Wadhera (2008) to calculate R_{max} and B as functions of the hurricane eye latitude, ψ, central pressure deficit, ΔP, and region. Two models to calculate R_{max} were recommended, one for hurricanes located in the Atlantic Ocean and one for hurricanes located in the Gulf of Mexico. The best-fit equation estimates for R_{max} for the Atlantic Ocean and the Gulf of Mexico are given by Eqs. (8.3) and (8.4) respectively.

$$\ln(R_{\max})_{Atlantic} = 3.015 - 6.291\left(10^{-5}\right)\Delta P^2 + 0.337\psi + \varepsilon_{Atlantic} \tag{8.3}$$

$$\ln(R_{\max})_{Gulf} = 3.859 - 7.700\left(10^{-5}\right)\Delta P^2 + \varepsilon_{Gulf} \tag{8.4}$$

where $\varepsilon_{Atlantic}$ and ε_{Gulf} are modeled as Normal (0, 0.441) and Normal (0, 0.390) respectively. The Atlantic Ocean estimate is used for all hurricane steps east of 80°W and the Gulf of Mexico estimate is used for all hurricane steps west of 80°W and north of 18°N. Equations (8.3) and (8.4) are combined through Eq. (8.5) to yield one statistical model to determine R_{max} at each step of every simulated storm.

$$R_{\max} = a_1(R_{\max})_{Atlantic} + (1 - a_1)(R_{\max})_{Gulf} \tag{8.5}$$

where a_1 is given by Eq. (8.6).

$$a_1 = \frac{\sum \Delta P_{Atlantic}}{\sum \left(\Delta P_{Atlantic} + \Delta P_{Gulf}\right)} \tag{8.6}$$

Prior to landfall, the Holland pressure profile parameter, B, is given by Eq. (8.7).

$$B = 1.7642 - 1.2098\sqrt{A} \tag{8.7}$$

where A is given by Eq. (8.8):

$$A = \frac{f \cdot R_{\max}}{\sqrt{2R_d(T_s - 273) \cdot \ln\left(1 + \frac{\Delta P}{P_c \cdot e}\right)}} \tag{8.8}$$

where R_d = gas constant for dry air, T_s = sea surface temperature (°K), and e = base of natural logarithms. After making landfall, B is modeled by Eq. (8.9).

$$B = B_0 \cdot \exp(a_2 t) \tag{8.9}$$

where B_0 = value of B at landfall, and a_2 is given by Eq. (8.10).

$$a_2 = 0.0291 - 0.0429B_0, \quad a_2 \leq -0.005 \tag{8.10}$$

After the surface air pressure is calculated using Eqs. (8.2)–(8.10), the surface air pressure gradient, $\partial P/\partial r$, can be calculated and substituted into Eq. (8.1). The gradient wind speed, V_g, then takes the form of Eq. (8.11) (Vickery et al. 2000b).

$$\begin{aligned} V_g = {} & \frac{1}{2}(c \cdot \sin\alpha - f \cdot r) \\ & + \sqrt{\frac{1}{4}(c \cdot \sin\alpha - f \cdot r)^2 + \frac{B\Delta P}{\rho}\left(\frac{R_{\max}}{r}\right)^2 \exp\left[-\left(\frac{R_{\max}}{r}\right)^2\right]} \end{aligned} \tag{8.11}$$

8.3.3 Rainfall Model

In this study, the rate of rainfall is assumed to be symmetric about the hurricane eye (as described fully below) calibrated using data from the Tropical Rainfall Measuring Mission, or TRMM (Huffman et al. 2010). TRMM is a joint mission between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). TRMM is a NASA satellite that records global precipitation estimates on an hourly basis at a resolution of 0.25° × 0.25°. The TRMM satellite has been in operation since 1998. Using information obtained by the TRMM satellite, the hurricane rate of rainfall can be estimated. We adopt the hurricane rate of rainfall model developed by Tuleya et al. (2007), given by:

$$RR(r, V_{\max}) = \begin{cases} RR_0 + (RR_m - RR_0) \cdot \left(\dfrac{r}{r_m}\right) & \text{for } r < r_m \\ RR_M \cdot \exp\left[-\dfrac{(r - r_m)}{r_e}\right] & \text{for } r \geq r_m \end{cases} \tag{8.12}$$

where V_{max} = the maximum surface-level gust wind speed, RR_0 = the rain rate at $r = 0$, RR_m = the maximum rain rate, r_m = the radius to maximum rain rate, and r_e = the radial extent of the hurricane rainfall. Using Eq. (8.12), the rain rate is modeled, in a Rankine fashion, as linear from the hurricane eye to r_m, and decays exponentially from r_m to r_e. Furthermore, Tuleya et al. (2007) determined the parameters in Eq. (8.12) can be modeled as linear functions of the storm intensity (maximum wind speed), using a least squares regression, as in Eqs. (8.13)–(8.16).

$$RR_0 = d_1 + e_1 U \tag{8.13}$$

$$RR_m = d_2 + e_2 U \tag{8.14}$$

$$r_m = d_3 + e_3 U \tag{8.15}$$

$$r_e = d_4 + e_4 U \tag{8.16}$$

where U = the normalized maximum 1-min sustained surface wind speed given by Eq. (8.17).

$$U = 1 + \frac{(V_m - 35)}{33} \tag{8.17}$$

where V_m = the maximum 1-min sustained surface wind speed given in knots. Assuming average maximum wind speeds for tropical storms, category 1–2 hurricanes, and category 3–5 hurricanes of 45 knots, 80 knots, and 115 knots, respectively, the coefficients d_i (i = 1, 2, … 4) and e_i (i = 1, 2, … 4) can be determined through regression of the historical TRMM satellite data. For any V_{max}, the hurricane rain rate can then be estimated at each time step and integrated over the hurricane track to obtain a total rainfall estimate. Figure 8.4 shows the actual total rainfall captured by surface rain gauges for the storms listed in Table 8.1 and the simulated total rainfall obtained for the same storms using the model outlined above. As shown, the overall rainfall distribution agrees quite well between the actual and simulated rainfall. Due to the resolution of the model, the simulated rainfall does not capture local maxima that appear in the actual rainfall (*e.g.*, maxima in South Carolina and the Florida panhandle). However, the totals for the majority of the coastline are in good agreement.

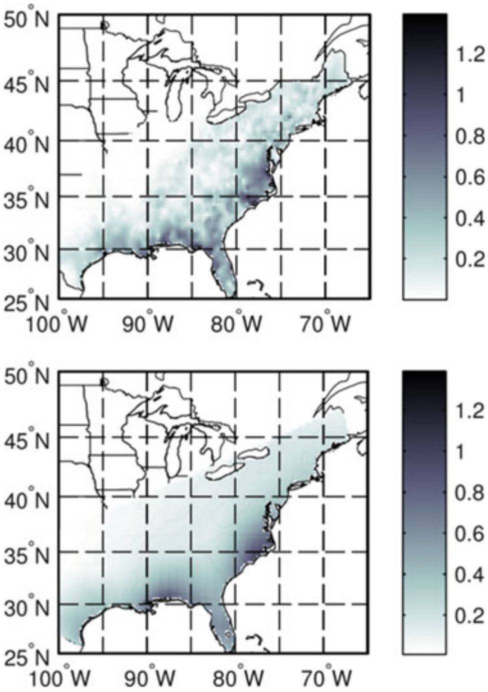


Fig. 8.4 Actual (*top*) and simulated (*bottom*) rainfall for storms listed in Table 8.1

Table 8.1 Storms included in rainfall totals of Fig. 8.4

(Year) Storm name			
1995 Allison	1998 Charley	1999 Harvey	2002 Isidore
1995 Erin	1998 Earl	1999 Irene	2002 Lili
1995 Opal	1998 Frances	2000 Gordon	2004 Frances
1996 Bertha	1998 Georges	2001 Allison	2004 Hermine
1996 Fran	1998 Hermine	2001 Barry	2006 Ernesto
1996 Josephine	1999 Bret	2001 Gabrielle	2007 Barry
1997 Danny	1999 Dennis	2002 Fay	2008 Hanna
1998 Bonnie	1999 Floyd	2002 Hanna	2011 Irene

8.3.4 Empirical Storm Tracking and Central Pressure Model

An empirical tracking model was proposed by Vickery et al. (2000b) to describe the hurricane translational wind speed and heading angle. In this study, the entire Atlantic basin was divided into $5^\circ \times 5^\circ$ grid blocks, as shown in Fig. 8.5. Each grid block has its own grid-based parameters that are used to determine the translational wind speed and heading angle at next time-step by Eqs. (8.18) and (8.19) respectively.

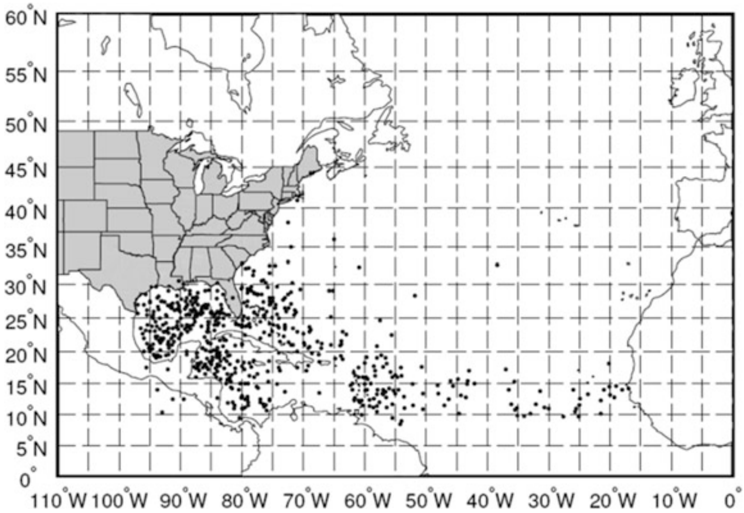


Fig. 8.5 Initial positions of US landfalling hurricanes in the HURDAT database and 5° × 5° grid division for the Atlantic basin

$$\Delta \ln V_T = a_1 + a_2\psi + a_3\lambda + a_4 \ln V_{T_i} + a_5\theta_i + \varepsilon \tag{8.18}$$

$$\Delta\theta = b_1 + b_2\psi + b_3\lambda + b_4 V_{T_i} + b_5\theta_i + b_6\theta_{i-1} + \varepsilon \tag{8.19}$$

where V_T = translational velocity (translational wind speed), θ = heading angle, a_i (i = 1, 2, ... 5) = coefficient for translational velocity, b_i (i = 1, 2, ... 6) = coefficient for heading angle, ψ and λ = storm latitude and longitude, V_{Ti} = translational velocity at time-step i, θ_i = heading angle at time-step i, θ_{i-1} = heading angle at time-step i − 1, and ε = random error term.

The HURDAT database contains data at 6-h intervals describing hurricane eye position, translational velocity, heading angle and central pressure for all hurricanes that have occurred in the Atlantic basin since 1851. Therefore, the coefficients a_i and b_i for each grid location can be determined through regression analysis of HURDAT data at each grid location. An analysis of the tracking parameters was performed in Mudd et al. (2014), in which two key conclusions were drawn. Firstly, there is a lack of evidence of climate-influenced changes in hurricane track characteristics. Secondly, through comparison of landfalling numbers and spatial behavior of hurricane tracks, it was shown that simulating hurricanes using tracking parameters based only upon historical US landfalling hurricanes (instead of all Atlantic basin hurricanes) maintains best agreement between simulated hurricane data and historical hurricane data.

Based upon these findings, tracking parameters in this study were determined from only those hurricanes that made landfall in the US from 1851 to 2012, and any impact of climate change on the parameters of Eqs. (8.18) and (8.19) was not considered in the simulation process. (*i.e.* the Markov model used in the tracking model of this study was assumed to be stationary.) For those grid locations with little or no hurricane data, the coefficients were assigned the corresponding values from the nearest grid location.

The hurricane central pressure model suggested by Vickery et al. (2000b) was developed based on the relative intensity concept (Darling 1991). The hurricane eye central pressure P_c can be expressed in terms of relative intensity I, and vice versa. The details of the relationship between hurricane eye central pressure and the relative intensity can be found in the appendix of Darling's paper (Darling 1991). Of particular interest in the present study is Darlings finding that the hurricane eye central pressure is a function of sea surface temperature as in Eq. (8.20).

$$\ln(I_{i+1}) = c_0 + c_1\ln(I_i) + c_2\ln(I_{i-1}) + c_3\ln(I_{i-2}) + c_4T_s + c_5\Delta T_s + \varepsilon \qquad (8.20)$$

where I_{i+1} = relative intensity at the time-step $i+1$; I_i, I_{i-1}, I_{i-2} = relative intensity at the time steps i, $i-1$ *and* $i-2$, c_i = the grid-based coefficient for relative intensity, T_s = sea surface temperature (°K), ΔT_s = difference in sea surface temperatures at time-steps i and $i+1$ (°K), and ε = random error term. Similar to the tracking model coefficients, the coefficient parameters c_i for each grid location can be determined by regression analysis, using the relative intensity values calculated from the HURDAT central pressure data at each grid location. For those grid locations with little or no hurricane data, the coefficients are assigned the corresponding value from the nearest grid location. After the hurricane makes landfall, the central pressure decays, and the relative intensity approach is no longer applicable. For the current climate, the T_s (SST) value is taken as the 2012 SST data, and for the future climate scenario, the value is taken as the 2100 SST data. Thus, the effect of climate change on storm intensity and size is explicitly considered herein.

8.3.5 Decay Model

Once a hurricane makes landfall, it is removed from its energy source (the sea) and it reduces in strength. Increased surface friction overland also decreases the intensity, further contributing to the decay. Consequently, both the central pressure difference and the rotational wind speed decrease according to some decay model. The decay model (Vickery and Twisdale 1995) used in this study takes the form of an exponential decay function as in Eq. (8.21).

$$\Delta P(t) = \Delta P_0 \cdot \exp\left(-\alpha_p t\right) \qquad (8.21)$$

where $\Delta P(t)$ = the central pressure deficit (mb) at time t after landfall, ΔP_0 = the central pressure deficit (mb) at landfall, a_p = site-specific decay parameter (constant), and t = time after landfall.

In Mudd et al. (2014) the site-specific decay parameter a was only a function of the central pressure deficit at landfall. Vickery (2005) found the site-specific decay parameter a_p (in some regions) is more accurately modeled as a function of not only central pressure deficit at landfall, but also translational velocity c and radius to maximum winds R_{max}. This study uses the functions of a_p as determined by Vickery (2005), which are given by Eqs. (8.22)–(8.25).

$$\text{Gulf Coast}: \quad a_p = 0.0413 + 0.0018\left(\frac{\Delta P_0 c}{R_{\max}}\right) + \varepsilon \quad \sigma_\varepsilon = 0.0169 \tag{8.22}$$

$$\text{Florida (East Coast)}: \quad a_p = 0.0225 + 0.0017\left(\frac{\Delta P_0 c}{R_{\max}}\right) + \varepsilon \quad \sigma_\varepsilon = 0.0158 \tag{8.23}$$

$$\text{Mid-Atlantic Coast}: \quad a_p = 0.0364 + 0.0016\left(\frac{\Delta P_0 c}{R_{\max}}\right) + \varepsilon \quad \sigma_\varepsilon = 0.0161 \tag{8.24}$$

$$\text{North Atlantic Coast}: \quad a_p = 0.0034 + 0.0010\Delta P_0 + \varepsilon \quad \sigma_\varepsilon = 0.0114 \tag{8.25}$$

where the error term ε is modeled as a Normal (0, σ_ε) variable.

8.3.6 Gradient to Surface Wind Speed Conversion

While the hurricane is inland, the surface wind speed, at a standard reference height of 10 m above the ground, can be estimated using conversion factors applied to the wind speed at the gradient level, generally taken as between 500 and 2000 m above the ground. Open terrain conditions are assumed when describing the surface wind speed at the standard reference height. The gradient-to-surface wind speed conversion factors assumed herein for both sustained wind speeds and gust wind speeds are taken from Lee and Rosowsky (2007).

8.3.7 Simulation Procedures

Simulated hurricanes start in the Atlantic basin with parameters based directly on a randomly selected US landfalling hurricane contained in the HURDAT database (*i.e*. initial location, angle, translational speed, and central pressure). The locations of hurricane formation for each event in the HURDAT database are shown in Fig. 8.5. The hurricane then moves along a track defined by the tracking and central pressure models. The hurricane's position at each subsequent 6-h interval can be determined by Eqs. (8.18) and (8.19) using the parameters derived from the information in the HURDAT database. Similarly, the next interval's central pressure (intensity and size) can be obtained using Eq. (8.20). Once the hurricane makes landfall, the central pressure decays according to Eq. (8.21). Finally, the gradient wind speed can be obtained from Eq. (8.11) and converted to a surface wind speed using the gradient-to-surface wind speed conversion factors found in Lee and Rosowsky (2007). If the simulated hurricane produces a significant maximum 10-min surface wind speed (defined herein as 15 m/s or greater) at any geographical location in the US Northeast, a rainfall estimate is obtained using Eq. (8.12), and the time-step is recorded in the wind speed time series for the zip code that encompasses it.

Following this procedure, 10,000 years of simulated hurricane events are generated for both the current and future climate scenarios, and the simulated hurricane wind speed records are developed for every zip code in the study region. Based on a framework developed by Wang and Rosowsky (2012), in which the hurricane wind speed and storm size are jointly characterized using the descriptors of maximum gradient wind speed V_{max} (at the eye-wall) and the radius to maximum wind speed R_{max}, extended herein to include rainfall rate, the values of these three parameters associated with the 10-year, 20-year, 50-year, 100-year, 300-year, 700-year, and 1700-year mean recurrence intervals (MRI's) are calculated. The results can then be compared, *e.g*., 2012 vs. 2100, to assess the impacts of possible future climate change effects on the hurricane intensity (wind, rain) and size.

Note that in the study region considered in this paper (the US Northeast coast), the extreme wind and rain climates may not be characterized by hurricane wind speeds and rainfall alone. Extra-tropical storms and thunderstorms also are expected to influence the extreme wind and rain climates. Therefore, the simulated hurricane wind speed and rainfall records developed herein can only be used (by themselves) to characterize the wind and rain hazard close to the coast where the extreme wind/rain climate is dominated by tropical storms (hurricanes). In addition, significant rainfall events are expected to be associated with hurricanes as this joint hazard was the focus of this research.

8.4 Results and Discussion

Consistent with earlier studies that analyzed the landfalling positions of hurricanes (Wang 2010; Lee and Rosowsky 2007), the simulated hurricanes were assumed to occur with equal probability along the length of coastline of the study area. The historical landfalling rate on the US Northeast coast is approximately 0.11 hurricanes per year. The simulated landfalling rate under the current climate scenario was approximately 0.12 hurricanes per year, which agrees well with the historical landfalling rate for the study region. Under the future climate scenario RCP 8.5, the simulated landfalling rate was also found to be approximately 0.11 hurricanes per year for the study region (*i.e*., no significant change). Figure 8.6 shows the nearest 6-h location of hurricane eye post landfall in 1000 years of simulated events for the US northeast coast under the 2012 climate scenario and the 2100 climate scenario RCP 8.5.

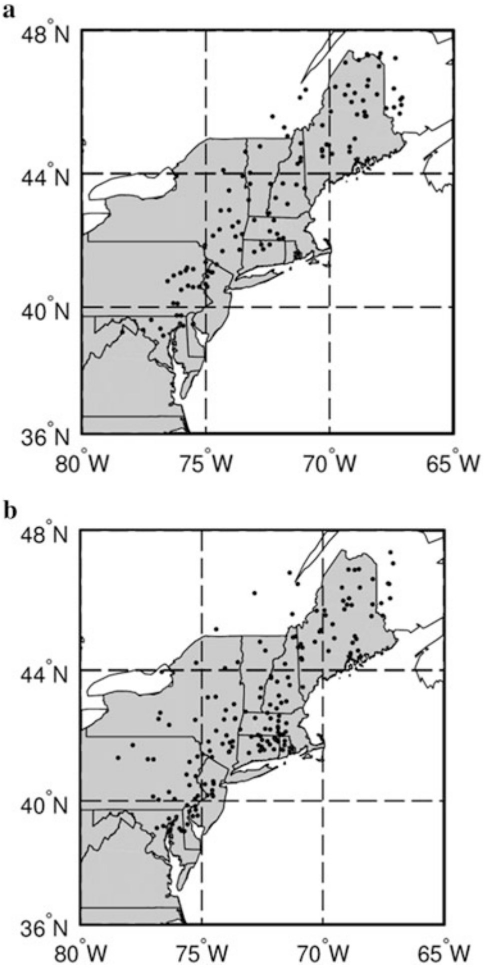


Fig. 8.6 Nearest 6-h location of hurricane eye post landfall in 1000 years of simulated events for the US Northeast coast under (**a**) the 2012 climate scenario and (**b**) the 2100 climate scenario RCP 8.5

The pairwise joint histogram, estimates of the pairwise probability of exceedance, and MRI's of the simulated events can be determined using the key descriptors V_{max}, RR_{max} (maximum rate of rainfall), and R_{max} (radius to maximum winds) of the closest 6-h interval post-landfall, using a framework developed by Wang and Rosowsky (2012). The pairwise joint histogram can be constructed using data pairs of V_{max} and R_{max} (RR_{max} and R_{max}) recorded at the time of landfall. The pairwise annual joint exceedance probability was obtained, using the pairwise joint histogram, by dividing the number data pairs of V_{max} and R_{max} (RR_{max} and R_{max}), within a specified bin, by the total number of data pairs recorded in the simulation and multiplying by the annual hurricane occurrence rate, λ. Once the pairwise annual joint exceedance probability was defined, pairwise hazard levels (with different annual exceedance probabilities) can be described by equi-probability contours. The pairwise hazard level can also be described as an exceedance probability in

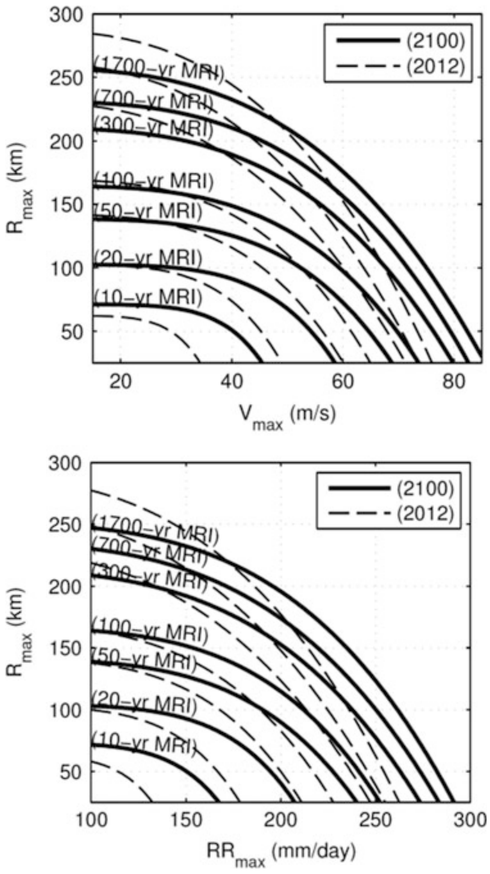


Fig. 8.7 Pairwise hazard level contours for the Northeast US coast under the 2012 climate scenario and the 2100 climate scenario RCP 8.5

N years (*e.g.* 2 %/50 years). The pairwise hazard level contours at the time of landfall corresponding to different MRI values or annual exceedance probabilities are shown in Fig. 8.7. This figure shows that under future climate scenario RCP 8.5 in the year 2100, the maximum wind speeds and maximum rates of rainfall associated with each hazard level are expected to increase, while the maximum size of the hurricanes associated with each hazard level remains relatively unchanged for lower hazard levels and decreases for larger hazard levels.

Expanding the framework developed by Wang and Rosowsky (2012) to three variables (*i.e.* V_{max}, RR_{max} and R_{max}) hazard level surfaces can be defined to assess concomitant hurricane hazards jointly. Figure 8.8 shows hazard level surfaces corresponding to ASCE 7-10 (ASCE 2010) Design Category I (15 % exceedance probability in 50 years, annual exceedance probability = 0.00333, MRI = 300 years), Design Category II (7 % exceedance probability in 50 years, annual exceedance probability = 0.00143, MRI = 700 years), and Design Category III/IV (3 % exceedance probability in 50 years, annual exceedance probability = 0.000588, MRI = 1700 years). In Fig. 8.8, for all hazard levels,

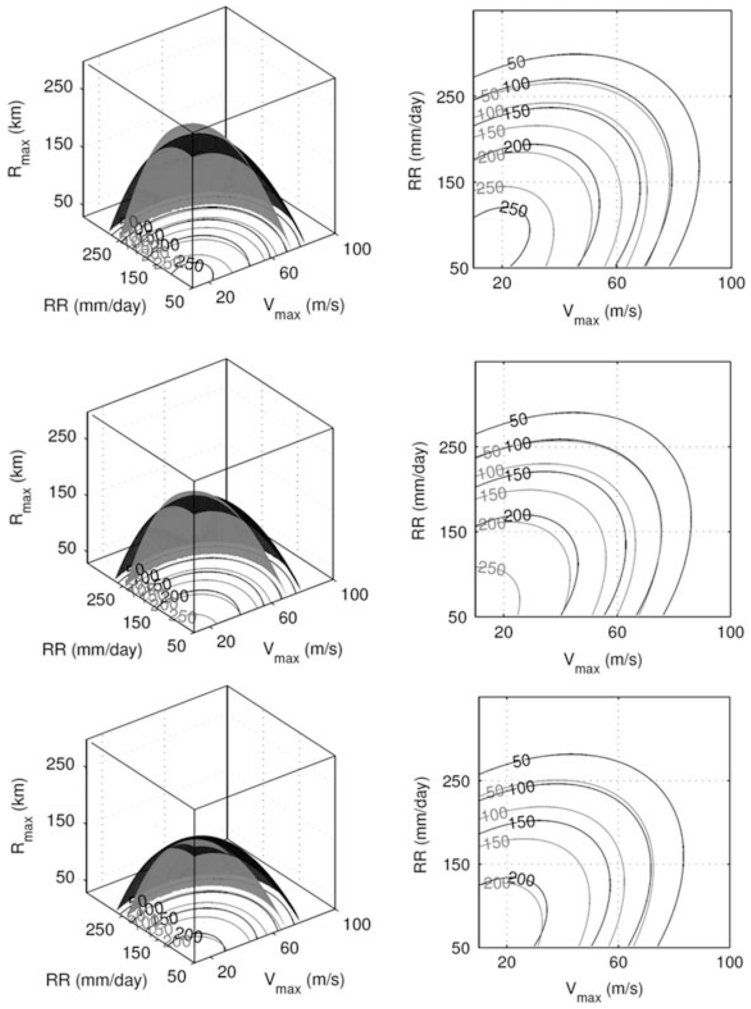


Fig. 8.8 Concomitant hazard level surfaces and contours for the northeast US coast under the 2012 climate scenario (*grey*) and the 2100 climate scenario RCP 8.5 (*black*) for the 1700-year MRI (*top*), 700-year MRI (*middle*) and 300-year MRI (*bottom*)

equal sized events are shown to have higher maximum gradient wind speeds and rates of rainfall when simulated in the future climate scenario compared with the 2012 climate scenario. The increase seen in maximum surface-level gust wind speeds and rate of rainfall is greater for smaller sized events than for events of a larger radius.

The simulated hurricane databases, for the current and future climate scenarios, were then used to create design wind speed maps, comparable to those in ASCE 7-10 (ASCE 2010). For every zip code in the study region, design wind speeds were calculated for design categories I, II, and III/IV, as defined in ASCE 7-10 (ASCE

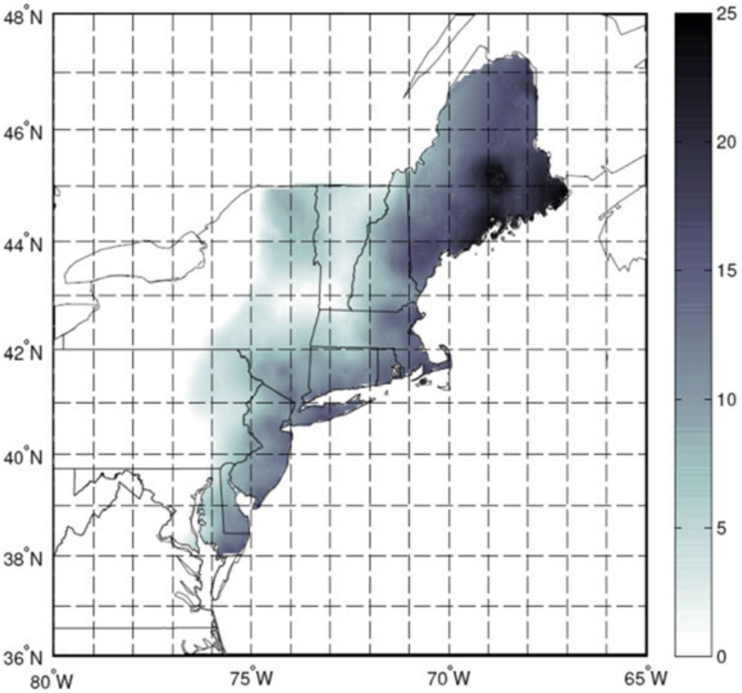


Fig. 8.9 Expected change (%) in design wind speeds between the 2012 climate scenario and the 2100 climate scenario RCP 8.5 for ASCE 7-10 Design Category II

2010). Figure 8.9 shows the difference in wind speeds, between the current climate scenario and the future climate scenario, for ASCE 7-10 (ASCE 2010) design category II. Design category II wind speeds correspond to a 7 % exceedance probability in 50 years (annual exceedance probability = 0.00143, MRI = 700 years). Based on the simulations performed herein, the majority of the Northeast US coastline is expected to see an increase of about 15 % in ASCE 7-10 (ASCE 2010) design category II wind speeds in the year 2100 compared to the year 2012, with some areas seeing an increase of up to 25 %. In addition, larger increases in design wind speeds were observed when considering more extreme MRI events.

8.5 Hazard-Consistent Hurricane Parameter Sets

Using figures such as Figs. 8.7 and 8.8, it is possible to extract characteristic parameter sets that can be used to define a hazard event (in this case, a hurricane). For example, considering the top figure in Fig. 8.7, one could extend vectors from the origin that intersects the hazard contours at coordinates defining (V_{max}, R_{max}) pairs at that hazard level. A set of (*e.g.*, equi-radial) vectors could define a set of hazard-consistent characteristic event parameters (or, in the case of joint hazard contours, characteristic events). Similar joint-variable and joint hazard studies have developed similar types of figures showing hazard contours (Rosowsky and Wang 2013; Wang and Rosowsky 2013) and further describe this concept and its relation to design (codes).

Hazard-consistent hurricane event (wind and rain) parameter sets could be coupled with storm surge and inland flooding models, for example, to provide information needed in performance-based engineering (design or assessment) applications, loss estimation studies, or spatial risk analyses considering the concomitant hazards of wind and surge/flood. Rosowsky and Wang (2013) have shown how bivariate hazard contours also can be used to calibrate load coincidence factors for existing (*e.g.*, LRFD) and emerging (*e.g.*, PBD) design philosophies.

8.6 Summary and Conclusions

Using state-of-the-art empirical, event-based hurricane models and considering one IPCC climate change scenario, an analysis was presented to incorporate the possible future climate change impact on the joint (concomitant) hurricane wind and rain hazard. The IPCC RCP 8.5 climate change scenario for the year 2100 is considered in this study. The US Northeast coastline is used as the study region, which sees the greatest increase in sea surface temperature (SST) under the RCP 8.5 climate change scenario. In addition to consideration of the influence of changes in SST in the gradient wind field and central pressure models (as in Mudd et al. 2014), this study also considers the influence of changes in SST in the decay model.

A total of 10,000 years of hurricane events, under both the current (2012) and future (2100) climate conditions, were simulated to produce a database of simulated maximum hurricane wind speeds for every zip code in the study region. The resulting database consists of information such as time of hurricane passage, maximum gradient wind speeds, maximum surface wind speeds, radius of maximum winds, as well as tracking information (latitude, longitude, translational velocity, heading angle) for every storm that made landfall in the study region. A rainfall model was adapted and linked to the wind model to create associated rainfall information (*e.g.*, the maximum rate of rainfall, total cumulative rainfall). Information on V_{max}, RR_{max} and R_{max} was extracted from the database to form the joint histogram, from which characteristic hurricanes corresponding to different hazard levels (MRI's) were able to be identified.

This study presents a framework that can be used to investigate the effects of climate change on the hurricane joint wind and rain hazard. Specifically, the effects of changes in sea surface temperature on the hurricane wind field (size and intensity) coupled with an associated rainfall were investigated. Our analysis indicates, across all hazard levels, under the future climate scenario RCP 8.5 in the year 2100, extreme hurricane events in the future may produce surface wind speeds and rates of rainfall substantially higher than those produced by extreme hurricanes simulated with the 2012 climate data. This suggests the need for an increase in design wind speeds in the future in order to ensure target safety and performance levels. However, as noted throughout the paper, the results herein only consider RCP 8.5 and its effects on the gradient wind field, central pressure, and decay models. In order to more accurately assess the effects of changes in SST on future hurricane hazard, any possible effects of SST on the hurricane genesis model (*i.e.*, annual hurricane occurrence rate, genesis location), the hurricane tracking model (*i.e.*, translational velocity, heading angle), and the rainfall model also must be considered. Furthermore, while SST is understood to be the dominant parameter controlling the behavior of hurricanes, several other environmental parameters (e.g., wind shear, relative humidity, tropopause temperature) are also likely to play a role in hurricane development and strengthening. Effects on the hurricane hazard due to future changes in these other parameters were not considered in this study. Since it is unlikely that SST is the only environmental parameter to vary with changing climate, the hurricane models presented here could be modified/extended to take into account these effects to characterize their impacts on future hurricane hazards. This work is on-going by the authors.

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Part III
Risk Evaluation: Theoretical Frameworks

Chapter 9
Deontology and Natural Hazards

Adam Hosein

Abstract In this chapter, I explore some fundamental moral questions about how we should evaluate disaster policy. I offer a challenge to the dominant approach, namely cost-benefit analysis, arguing that we need to give weight to some crucial moral distinctions that this approach ignores, such as the difference between doing and allowing harm. In place of cost-benefit analysis, I defend an alternative “deontological” approach, which incorporates these distinctions. But I also show that more work is needed to fully develop a deontological theory of disaster policy. There are fruitful new avenues in this area for both policy analysts and moral theorists.

9.1 Introduction

Policy choices and engineering decisions have a large impact on what risks natural hazards pose to people (Murphy and Gardoni 2011). For instance, our construction choices significantly affect what impact earthquakes will have on people’s lives and property. In this chapter I want to consider whether the ethics of imposing harms can help us evaluate these actions. In particular, I’ll try to apply deontological ethical theory, according to which there is a strong duty not to inflict harm on others. This approach provides an important alternative to cost-benefit analysis (and other forms of consequentialism) by looking at not just the outcomes of our actions and policy choices, but also how we treat particular people.

On the face of it, the deontological approach has serious limitations in this context. For instance, disaster policy presents situations where we aren’t simply harming people but exposing them to risks of harm. And it’s not clear that our actions can be easily described as inflicting harm, in the way that deontologists are usually concerned with.

I’ll argue that despite these initial problems there is still some promise for a using a deontological approach. But I’ll also show that trying to apply deontology in

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this context raises a host of new questions that need more extensive theoretical treatment. For instance, it shows that we need to make several new distinctions between different ways of wronging people. I will proceed as follows. In Sect. 9.2, I will define deontology and show how it is a departure from consequentialism and the familiar cost-benefit analysis of risk. In Sect. 9.3, I will argue for a particular version of deontology and show how it can be applied to probabilistic situations. In Sect. 9.4, I turn to applying the deontological framework to our dealings with natural hazards and will raise some questions and problems. In Sect. 9.5, I offer some initial answers to these questions and problems but also illustrate some areas where much more work is needed. Section 9.6 concludes.

9.2 What Is Deontology?

The best way to understand deontology is by contrast with the most familiar framework for thinking about risk, namely consequentialism and its operationalized descendent, cost-benefit analysis. According to act consequentialism, we should choose the action, of those available to us, that would produce the best possible consequences.[1] Suppose that there are three acts available: A, B, and C. Each of these acts, if performed, would produce a particular outcome: X, Y, and Z, respectively. According to the consequentialist, these outcomes can be ranked as better and worse. The right action is the one associated with the highest ranked outcome.

Now, for the theory to be useful in evaluating our actual behavior-for instances, choices about how much to invest in maintaining levees or what construction methods to use-we need a way of ranking various outcomes. Utilitarians, for instance, rank outcomes by looking at the sum of the happiness experienced in those outcomes. In current policy analysis by economists, risk analysts, and so on the most familiar approach is to evaluate outcomes is by first assigning dollar values (typically by relying on “willingness to pay” measures) to various goods and bads, such as births and deaths, and then aggregating to assign a dollar value to each outcome.[2] Thus, “cost-benefit analysis” (CBA), as this approach is known, is a consequentialist framework.

As I have described consequentialism so far, the theory assumes that each action is determinately associated with just one outcome. But of course in practice we are typically dealing with probabilistic situations, where the outcome of any given action is not known with certainty. A more complicated theory will be needed if we are to apply consequentialism to the imposition of risk, my focus in this paper. Take, say, the following example:

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[1] For further discussion of consequentialism see Sinnott-Armstrong (2011).

[2] See, for instance, Adler and Posner (2006) for further explanation of this approach.

House: I am building a house in a dense urban area and considering different construction methods. Using cheaper construction methods will create a greater risk of a brick becoming dislodged and hitting a pedestrian.

Act consequentialism does not tell us what to do here, because we do not know which outcome will be produced by the various available acts and so we do not know which act would produce the best outcome. What can the consequentialist do? The standard revision is to say that in probabilistic contexts we should *estimate* the value of the outcome any given act would produce. And we do that by looking at its expected value: the weighted average value of the various possible outcomes associated with that action (where each outcome's value is weighted by its probability). Cost benefit-analysis similarly involves looking at the expected (dollar) costs and benefits of the various outcomes we might produce.[3]

Now, there's a moral distinction that plays a large role in our common-sense ethical thinking which is not given any fundamental weight in a consequentialist theory or in standard cost-benefit analysis. To see the distinction, it is helpful to consider a simple example like the following:

Driver: Five people are in danger of drowning. You can save them (and this is the only way to save them) by driving down to the shore and pulling them out of the water. But to get there in time to save them you would have to run over, and thereby kill, a single person who has fallen on the road and broken his leg.

If you drive to the shore the number of lives lost will be 1, whereas if you don't drive to the shore the number of lives lost will be 5. So, consequentialism on its face recommends driving to the shore. But most people don't think this is morally permissible. To get to the shore you would have treat the person with a broken leg very badly: you would have to kill him. And this is impermissible even though it would result in a net four lives saved.

We can explain these common sense reactions by relying on the doing-allowing distinction.[4] In particular, we can say that you treat someone worse when you *do* harm to them-as when you kill the one-than when you merely *allow* harm to befall them-as when you fail to save the five. If good consequences were all that mattered, then we would expect people to judge that you are permitted (and indeed required) to drive to the shore, despite the harm you would have to do to the one. But, since they don't judge this, it seems that we care about more than just producing good

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[3] As described in, for instance, Adler and Posner (2006, Chap. 3).

[4] Of course, there is huge debate about whether this is a good explanation or whether we should take seriously our common-sense judgments. It is well outside the scope of this paper to offer a full defense of the distinction: I'm just trying to explain the basic motivation.

consequences: we care about the fact you would have to *treat* them one person very poorly. In fact, the case just described suggests that it is intuitively at least five times worse to kill someone that to fail to save a life, since you may not kill the one even to save five other lives.

Deontological theories, as I will define them, incorporate this distinction.[5] They hold that there are constraints on acting to produce the best consequences, because we are bound by duties not to harm others.[6] What I want to consider in this paper is whether theories of this kind can help us understand the duties of governments and individuals with respect to natural hazard risks.

9.3 Which Version of Deontology?

Before moving on, we need to distinguish two different kinds of deontological view, because they have very different implications for how just how constrained we are in harming others and because they deal very differently with risk (Alexander 2000). The first, "absolutist deontology," says that one may never inflict harm on someone else, whatever the benefits of doing so. The second, "threshold deontology," says that inflicting harm on someone carries substantially greater (negative) moral weight than failing to produce a comparable benefit for others. Thus, the threshold deontologist says that there is some number of lives such that you would be allowed to kill one person to save those lives, whereas the absolutist denies that there is any such number. According to threshold deontology, inflicting harm is K times worse than failing to produce a comparable benefit.[7] Thus, if an action would inflict harm of degree H and produce a benefit of degree B threshold deontology says the following (Zamir and Medina 2010):

TD (threshold deontology): An action is permissible only if $B > KH$.

Which version of deontology should we adopt? Our ultimate concern here is with risky situations, where the outcomes of our actions are unknown. And for familiar reasons absolutism seems to yield very implausible results in these situations. According to the absolutist, harming someone is infinitely worse than failing

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[5] They also often incorporate other related distinctions, such as the intending/foreseeing distinction, but in this paper I will focus on just the doing/allowing distinction, which is less controversial.

[6] The language of "constraints" comes from Nozick (1974)'s discussion.

[7] Zamir and Medina (2010) ask whether the relevant function involves a multiplier, K, rather than, say, a fixed factor F that one adds to the harm. I chose the first function simply because I think it fits people's judgments about the various examples better. When we consider cases that involve inflicting greater and greater harm, the benefits required to morally outweigh the harm seem to scale up proportionately.

to help someone else. Suppose you are in a situation where there is some small chance that your actions will harm someone else. How should the absolutist take into account the fact that the harm is merely possible rather than certain? A natural approach, given how grave the absolutist thinks it would be to inflict harm, would be to prohibit actions that have any non-zero chance of inflicting harm. But as Hansson (2013) and Huemer (2010) point out, this approach would rule out much of our everyday behavior: for instance, driving your children to school in a well-maintained car while taking great precaution still carries some risk of killing a pedestrian. It's extremely implausible to say that all of these actions are impermissible.

The absolutist could say here that an action is impermissible only if its probability of harming someone is above a sufficient level p. But this leads to implausible results also, even setting aside the difficult issue, which will discuss later, of how to choose thresholds in moral theory (Huemer 2010; Jackson and Smith 2006). Let's say that the cut-off probability $p = 0.4$. Suppose that there are three actions available to me:

- Action 1. Shoot at person A, exposing her to 0.39 chance of death.
- Action 2. Shoot at person B, exposing him to a 0.39 chance of death.
- Action 3. Shoot at both at once, exposing each to a 0.39 chance of death at the same time.

Let's suppose each of these actions would produce a substantial (and equal) amount of good (perhaps they are each unwittingly carrying a virus that will otherwise spread). And let's suppose that the relevant probabilities are independent: B's chance of dying is unaffected by whether or not A is killed (and vice versa). Since $0.39 < 0.4$, Action 1 is permissible and so is Action 2: in neither case am I doing something that has a probability of killing someone that is greater than the proscribed level. Moreover, Action 1 is permissible whether or not I perform Action 2, because the probability that I will kill A remains the same whether or not I perform Action 2. (Similarly, Action 2 is permissible whether or not Action 1 is performed.) However, Action 3 is impermissible: Shooting at both A and B carries a greater than 0.4 probability of killing someone and thus is not permitted.

The combination of these three claims about the permissibility of Action 1–3 is hard to accept. For instance, suppose that I have already (permissibly) shot at A. Since the relevant chances are independent, it is also permissible for me to subsequently shoot at B, exposing him to a risk of death of 0.39: still below the proscribed level. Yet while I can shoot at A and then immediately afterwards shoot at B, it is unacceptable for me shoot at them both simultaneously. How can that be? Surely the difference between killing them one after the other and killing them simultaneously is not morally significant (Jackson and Smith 2006)?[8]

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[8] Someone might say here that there is some arbitrariness in the distinction between performing two separate actions together, Actions 1 and Action 2, versus performing the single Action 3: for instance, maybe when I shoot at B quickly after shooting at A I can just as easily be said to have

More generally, the version of absolutism we have been considering-which incorporates a cut-off probability level-violates the following plausible principle:

> *Two Rights Don't Make a Wrong*: If it is appropriate for *S* to do *A* whether or not *S* does *B*, and it is appropriate for *S* to do *B* whether or not *S* does *A*, then it is appropriate for *S* to do *A* and *B*. (Huemer 2010, p. 337).

The form of absolutism we are considering, along with the very plausible *Two Rights* principle, entails that Action 3 is both permissible and impermissible.[9] Moreover, this kind of contradiction will arise in the wide range of circumstances where we impose independent risks on different people. For instance, any workable criminal justice system will almost inevitably punish some innocent people in a given year, even if the risk of punishment it imposes on any particular individual innocent is relatively low: the risks imposed on each of the many individuals tried will add up to a high probability of punishing *some* innocent person during the year (Huemer 2010; Hosein 2014). The absolutism we are considering must say that each fresh trial is acceptable, but the year's worth of trials is not.

Since absolutism is a non-starter as a theory of how to act in risky situations, it seems we must turn to threshold deontology. But is this move simply ad-hoc? If absolutism is independently the more plausible version of deontology, then perhaps we should just conclude that deontology has nothing to say about risk or must be rejected entirely because of its implausible consequences with respect to risk.

Fortunately, there are also independent reasons to choose threshold deontology over absolutism. Harms come in varying degrees and common-sense morality suggests that even inflicting a relatively small harm, such as a broken toe, is worse than allowing someone to suffer a broken toe: the doing/allowing distinction applies even when we considering these comparatively small harms. But it is surely at least *sometimes* permissible to inflict these harms. If the only way to save five people were to break someone's toe, then surely I would be permitted (and perhaps even required) to break it. So threshold deontology seems to provide the right account when it comes to inflicting relatively small harms. And once we have established this, it is also plausible to think that even larger harms can be inflicted with a sufficiently good justification. Larger harms, such as the loss of a leg or a shortened life span, seem to make people worse off by a non-infinite degree. So inflicting them should be morally worse by some non-infinite degree and thus should just require a justification which is however many times greater.[10]

Now, suppose that we adopt threshold deontology (from this point onwards, I will just say "deontology," assuming the threshold version unless I say otherwise), how exactly shall we deal with risky situations, which are our main concern here? I

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performed Action 3. But this is no help to the absolutist. It just suggests the unhappy implication that (according to absolutism) the same behavior can be permissible under one plausible description, yet impermissible under another equally plausible description.

[9] For an interesting way of denying the *Two Rights* principle, see Aboodi et al. (2008), but see also Huemer's reply (Huemer 2010, pp. 345–347).

[10] See also Alexander and Moore (2012) for further problems with absolutism.

said earlier that according to the threshold deontologist there needs to be a certain ratio between the harms we inflict and the benefits that we will produce:

TD: An action is permissible only if $B > KH$.

What are we to do in situations where B and H are not known with certainty? Well, as we saw earlier the standard approach taken by consequentialists in such circumstances is to estimate the relevant values by considering their expected value. Similarly, then, the deontologist can estimate the values of B and H by looking at their expectations, $E(B)$ and $E(H)$. Thus, to deal with risky situations they can adopt expected threshold deontology (Zamir and Medina 2010):

ETD (expected threshold deontology): An action is permissible only if $E(B) > K \times E(H)$

Let me sum up this Section so far. I have argued that the most attractive version of deontology is threshold deontology, which gives more plausible answers in risky and non-risky contexts. It is worth pointing out here where threshold deontology does and does not involve a departure from consequentialist thinking and cost-benefit analysis. According to the deontological view that I have been defending, the overall outcomes of our actions are certainly relevant to their assessment, even in cases where we are contemplating inflicting harm. And in the process of weighing various benefits, harms, and so on we might still use monetary scales to measure magnitude, as in standard cost-benefit analysis (though it is also open to the deontologist to use a different measure, such as effects on pleasure/pain, set backs to capabilities, and so on: deontology as I have defined it is agnostic on this question of measurement).

I think this degree of continuity with standard policy analysis tools is an advantage of the approach I have been defending.[11] While common sense morality seems to push us away from unqualified cost-benefit analysis, it is often claimed that alternatives are unable to deal with the problems that arise when we try to actually evaluate policy, especially the need to manage trade-offs and to do so in a way that allows for numerical comparisons.

Does this mean that threshold deontology isn't really any kind of departure from consequentialism? Barbara Fried (2012), for instance, argues that deontologists who reject absolutism end up adopting a standard of "due care" that is essentially "indistinguishable" from what CBA recommends, since it involves considering both the probability that our actions will cause harm and weighing that against the likely benefits of our actions. We have seen that Fried's claim is too quick. We can take into consideration the relevant probabilities and the size of any potential

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[11] For a similar perspective, see Zamir and Medina (2010).

benefit without thereby adopting CBA (or consequentialism more generally), since we might be incorporating the doing/allowing distinction.[12] This isn't a trivial difference.

Incorporating the doing/allowing distinction has large implications in other contexts, affecting the permissibility of torture and death penalty, the criminal process standards we should adopt, and so on.[13] For instance, constraints on doing harm make it much harder to justify torturing people, even in circumstances where it can yield useful information, because it is worse for us to torture someone ourselves than to fail to save some people whom the torture might help us protect. And they can help explain why we require high standards of proof in criminal trials: we are especially concerned to avoid punishing innocent people ourselves, even where this comes at some potential cost in preventing or deterring future crime that would harm innocents. We should expect the doing/allowing distinction to have similarly large implications for the risk management of natural hazards.

9.4 Can We Apply Deontology to Interactions with Natural Hazards? Some Initial Problems

Let's suppose we agree that there is some attraction to (threshold) deontology. Is it any use to us in thinking about natural hazards?

There are a wide range of actions performed by the government and private actors that affect people's exposure to natural hazard risks (Murphy and Gardoni 2011). For instance, decisions about whether and how to build dams and levees affect people's exposure to flood risks. Choices in housing design and construction affect exposure to earthquake risks. Instituting proscribed burns affects future risks from forest fires, but also carries its own risks. Given the impact that these actions can have on people's exposure to risk, we might expect the morality of risk imposition to have an important bearing on them. Plausibly, the duty not to inflict harm (or expected harm) bears on actions that alter people's risks exposure.[14] But is the deontological framework really helpful? There are several initial problems.

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[12] The resulting theory will of course still retain some of the basic structure of CBA/consequentialism, requiring us to quantify and consider the costs and benefits of our actions. But I think this is to be welcomed: it shows that we can take all of these factors into account even while weighing them in a manner that respects deontological distinctions. Deontologists can take advantage of the attractively quantitative approach to policy analysis of CBA/consequentialism without accepting all of its dictates.

[13] For discussion of these examples see Zamir and Medina (2010) and Hosein (2014).

[14] See Murphy and Gardoni (2011) for a more extensive argument that familiar duties from common-sense morality and the law have an important bearing on dealing with natural hazard risks.

9.4.1 Directness and Responsibility

The first problem concerns the precise relationship between those who bear the risks associated with natural hazards and the actions we take that affect those risks. Deontology is a theory of when it is permissible to *do harm to* or *impose harm on* someone else. In Driver, for instance, running over the one would clearly involve doing harm to her. In contexts that involve risk we don't know with certainty whether our actions will do harm to others, but deontologists are still typically concerned with risks that we directly *impose* on people. For instance, in House I am doing something—building the house—that imposes new risk on various future passersby.

Some of the actions we are ultimately concerned with in this paper do seem to involve doing harm to others or creating new risks to them. For instance, in instituting a prescribed burn, the Forest Service sometimes creates a risk of harm to those who live in nearby communities (and where that risk is actualized, resulting in losses of property and so on, we can say that the Forest Service harmed those people). But they typically involve changing the world in some way that affects the likelihood of an independent threat, such as an Earthquake, causing people harm (Murphy and Gardoni 2011). For instance, engineering decisions about how to build will typically affect the likelihood of an Earthquake causing losses of life or property. Building a dam or making decisions about how to maintain a levee will affect the chance that people will be living near to the water source and whether it will cause flooding. Decisions about to regulate the energy infrastructure will affect the impact of various natural hazards on people's lives, including the potential for energy blackouts and the knock-on effects of those blackouts on other parts of the infrastructure.

In none of these cases does the relevant actor seem to be simply creating a new risk of harm, as when one person plays Russian roulette with a gun to someone's else's head.[15] But in each of them cases the actors involved are doing things that affect that risk exposure of other parties, by modifying the impact that "natural" occurrences will have on those people. And this involvement with the relevant risks seems to be morally relevant. We cannot say that the actors are simply imposing those risks, but I think we can plausibly say that they bear (some) *responsibility* for those risks and any harms that eventuate. And preventing or protecting people from those risks plausibly carries greater moral weight than preventing or protecting

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[15] We shouldn't draw this contrast too sharply, though, because even apparently clear cases of "non-natural" risk also involve some interaction with the natural world. For instance, in describing the House example, I said that using certain materials would create a risk of a brick eventually becoming dislodged and striking a pedestrian. It's natural to think of this as a situation where the (potential) risk is due to factors solely internal to the structure and thus as a situation where by building the house I simply create an entirely "non-natural" threat. But really the source of the risk includes not just facts about the internal structure of the house but the way that it is likely to interact with ordinary wind, rain, subsistence, etc. So there relevant difference is probably one of degree.

people from risks that we do not bear responsibility for. For instance, if you are inviting people to rely on your construction work, you must take extra care to ensure that it doesn't expose them to risks associated with Earthquakes. And the state must take extra care to consider, say, flood related harms if approves housing development near to a river.

In sum, we can apply deontology to our interactions with natural hazards, but only if we switch from thinking just about risks that we *impose* on others to thinking more broadly about risks that we bear some *responsibility* for. Someone who is a responsible for a risk must take steps to mitigate or compensate those subjected to it, even though they did not impose that risk themselves. For instance, if I fail to warn you about some severe flooding on the road ahead, even though I can easily do so, then I bear some responsibility for your risk of drowning, even though I did not create the flood or the risk. I ought to chase after you and tell you to turn back.

Different kinds of involvement with a risk will plausibly carry with them different degrees of responsibility. For instance, a local government whose zoning decisions ultimately results in property damage due to wildfires is surely less responsible for that damage than someone who simply set fire to the houses would be. So, when we switch to thinking in terms of responsibility for risks rather than risk imposition we must consider a range of new and hard questions about much responsibility is generated by each of the various possible ways of being involved with a risk.

9.4.2 Multiple Agents

Questions about responsibility are also complicated in the cases where we are concerned with by the fact that multiple agents are often involved in the creation or maintenance of the risks.[16] In Driver, a single agent would be responsible for any harm to the one, and in House a single person—the owner and builder of the house—would be responsible for any risk to pedestrians. By contrast, in the management of natural hazards several agents are typically involved. Take, for instance, flood risks to people who live near to a river. And let's suppose that the federal government owns and maintains a nearby levee, local governmental agencies make zoning decisions about how near homes and businesses may be to the estuary, and individuals make decisions about where to live and work.[17] Each of these actors will have an impact on the likelihood of people being harmed by

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[16] Farber et al. (2009) give many examples of legal disputes surrounding disaster hazards where multiple institutions and actors are involved and the difficulties of assigning legal responsibility in these cases.

[17] See Cranor (2007) and Hansson (2013, Chap. 7.2–7.3) for further discussion of the role of individuals in exposing themselves to risk.

flooding. Who ought to bear the costs of preventing and insuring people against these risks?[18]

To answer these questions from within a deontological framework we again need to extend the framework somewhat. What is needed is to again rely on the idea of responsibility for a harm or risk. Generally speaking, multiple agents can be responsible for the same risk even if only one of them (or, as we saw in the previous section, none of them) imposes it. For instance, suppose that someone plans to light a fire in a forest, creating a risk to nearby home-owners. If I offer that person encouragement, then I am surely somewhat responsible for any ensuing risk, even though I am not the one to actually light the fire and impose the risk.

In the disaster policy contexts that we are concerned with, such as the flood example discussed earlier in this section, we must decide how to *divide* responsibility between the different agents involved. Having done so we can see how each actor should behave given her individual responsibility for the relevant risks. This approach of course raises the question of exactly how we should divide this responsibility between the actors. Applying a deontological framework to dealing with natural hazards, demands that we face hard questions about how to divide responsibility for risks among the various agents involved.

9.4.3 Expected Sufferers and Expected Beneficiaries

In the standard examples that motivate deontology, we are considering inflicting harms (or perhaps risks of harm) on members of a smaller group for the sake of benefits that will accrue to members of a larger group. The deontologist asks us to consider whether those benefits to the many are sufficient to justify mistreating the few. In Driver, for instance, we are asked to consider running over the one for the sake of saving the five. But thinking about natural hazards requires us to ask how we should evaluate situations where the people who are expected to be harmed by our actions are also among those who are expected to benefit from those actions (though not all natural hazard examples are like this). For instance, when the forest service institutes a proscribed burn, the people who are put at most risk are typically those who live closest to the burn area. But these people are also among the expected beneficiaries of the burn, since, if all goes well, it will prevent future forest fires from harming them by reducing the amount of nearby hazardous fuel. (There may also be other expected benefits from the burn, such as protecting natural resources or improving wildlife habitats). Or consider a zoning decision that allows people to live nearer to a flood plain. Although this means those people will be exposed to greater flood risk they may also benefit from access to cheaper housing.

This difference between Driver and the natural hazard examples just mentioned seems relevant. Surely it is easier to justify exposing someone to a risk when they

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[18] Chapter 15, in this book.

themselves would be among the expected beneficiaries of imposing the risk. This suggests that when we are considering the proportionality calculation recommended by threshold deontology (considering whether the expected benefits of our actions are sufficiently weighty relative to the expected harms) we should give some extra weight to potential benefits to the people who might be harmed by our actions. Thus, more weight should be given to the interests of people who might actually lose a home due to a proscribed burn than to the interests of people who live further away but might benefit from say the preservation of natural resources.

To summarize this section's findings, we have seen that some initial problems with applying deontology to natural hazard management can be dealt with by complicating the deontological framework, namely by recognizing the different ways of being responsible for a risk, recognizing that responsibility must sometimes be divided between multiple actors, and calculating overall benefits in a way that is sensitive to facts about who may be harmed by our actions. But these extensions to the framework also require us to face a host of new questions. We need to lay out the different types of responsibility for a risk and think about which actions create greater degrees of responsibility than others. Where multiple actors are involved, we need to think about how to divide responsibility for a risk. And when we are thinking about some of the benefits associated with a risk, we need to consider how much greater weight (if any) to give to the benefits that may accrue to those who are subjected to the risk. These questions have been given relatively little attention in the existing theoretical literature and my main proposal is that they deserve greater attention in future research.[19] By exploring these subtleties, we may be able to get closer to a theory of risk management that retains some of the basic structure and clarity of cost-benefit analysis while incorporating distinctions that drive the way members of the public think about harming and risk. I cannot carry out much of that work here, but in the next section I would like to address one major source of skepticism about this research program.

9.5 Thresholds, Weights, and Arbitrariness

I have argued for and attempted to apply threshold deontology, the version of deontology that says you may inflict (expected) harm on someone for the sake of producing a sufficiently large (expected) benefit. More precisely, the benefit must be some constant K times larger than the harm that would be produced. This of course raises the question: where is the threshold? Or, equivalently, what is the value of K? To evaluate policies and so on we need to settle this question, but a familiar complaint about threshold deontology is that it has no good answer to offer.

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[19] Though, as I have noted, there are important relevant discussions in Cranor (2007), Murphy and Gardoni (2011), and Hansson (2013).

The usual way of putting this objection is to say that there is no non-*arbitrary* way of selecting K.[20]

This concern is potentially exacerbated by the considerations I raised in the previous section. For instance, suppose we agree that there are multiple ways to be responsible for harms or risks—directly inflicting risks, making regulatory decisions that increase people's risks exposure, and so on—and that some of these ways create more responsibility than others. This suggests that we in fact need a set of constants $\{K_1, K_2, \ldots, K_n\}$ corresponding to the various ways of being involved with a harm. For instance, perhaps to justify directly creating a threat to someone you would need to produce a benefit that is K_1 times larger than the harm. Whereas, to justify merely authorizing building in an area that might expose people to flood harm you would need to produce a benefit that is K_2 times larger than the (expected) harm, where, presumably, $K_2 < K_1$.

This means that we need to settle not simply the value of one constant K but all of $\{K_1, K_2, \ldots, K_n\}$. The critic will likely say that these decisions will involve us in even more arbitrary decision making in choosing these values.

Can we avoid arbitrariness here? And if so, how? One choice is to set the various K values at 1, so that, for instance, doing harm to someone carries just the same weight as failing to help someone. To adopt this approach is just to return to the consequentialist/cost-benefit approach to the ethics of harming, caring only about the aggregate amount of benefit versus harm that our actions produce. But is this choice of K values less arbitrary than any other? The only reason to think so is if we already accept a full consequentialist theory (I will return to this possibility shortly).[21]

What the deontologist must rely on here, it seems, is a set of judgment calls: she must consider the various factors involved for herself and just decide which trade-offs seem appropriate. For instance, she will have to simply make a judgment of, for instance how many lives saved we should be willing to trade for having to inflict harm on an individual. In the familiar philosophical jargon, she will have to rely on her "intuitions."

Is this use of intuition objectionable? Those who are concerned about arbitrariness will say that using intuition in this way is precisely the kind of arbitrary choice that they reject. And they will say that it is particularly inappropriate for public policies and decisions to reflect such individual judgment calls.

I will suggest several responses to this concern. First, consider again how deontology is motivated in the first place. We arrive at the deontological view by

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[20] For instance, Posner and Vermeule (2006, p. 40) complain that threshold deontology has an "arbitrary flavor" and Alexander and Moore (2012) raise the same objection. In the context of risk evaluation, see Hansson (2013, Chap. 2.3) for a similar concern that the deontologist doesn't have a full theory of how to make trade-offs.

[21] It might be said that Scanlon (1998)'s contractualism is an important alternative, but I'm skeptical about the theory as a whole and it would also still require a lot of use of intuition to make trade-offs, of the kind that I am about to describe. See Hosein (2013) for elaboration of both of these issues.

noticing that certain actions seem to be wrong, such as those in Driver and House. And we make these observations by relying on our ordinary capacities for moral judgment: our intuition, in other words. So, if it is unproblematic to use intuition in this way, I don't see why it should be any more problematic to use intuition to work out which trade-offs are permissible. If we use intuition to discover that it is *worse* to do than to allow harm, then why can't we use it to also discover *how much* worse it is? Of course, some people will reject the use of intuition at all, but there doesn't seem to be any special problem for threshold deontology, which requires its use to make trade-offs.

Second, to the extent that the use of intuition is a problem it seems to arise for not only deontological views but for many of the most plausible consequentialist views too.[22] I have been discussing consequentialism as if that view was concerned solely with the effects of our actions on the aggregate of people's welfare. And this is the kind of consequentialism typically adopted by those who engage in cost-benefit analysis. But for familiar reasons this kind of consequentialism seems to leave out some very important considerations. It forces us to look at only the *sum* of individual welfare (and other goods), ignoring how that welfare is *distributed*. But most of us have distributive concerns about, for instance, how unequal the distribution of welfare is, whether each individual is doing sufficiently well, and so on. Thus, it is very common to adopt versions of consequentialism that give some weight to these concerns by including a factor that reflects the degree of inequality (egalitarianism), gives extra weight to benefits to the less well-off (prioritarianism), or special weight to ensuring that each person leads a decent life (capability or sufficiency views).[23] These views require us to make judgments call about just *how much* weight to give to equality and so on.

The responses so far have shown that there is nothing very special about threshold deontology in its reliance on intuitions. I think the charge of arbitrariness can also be answered more head on. Although the deontologist does not have a fully theory to offer of where various trade-offs should be made, that doesn't mean our use of intuition is completely unguided by reason. The relevant distinctions drawn by the deontologist, between merely allowing harm and the various ways of being more responsible for harm, not only affect our responses to examples—such as House—but also seem on reflection to be morally relevant. For instance, it does seem plausible that I am more responsible for harms (or risks) that I directly inflict on other people than harms that merely befall them. And, similarly, it also seems plausible that I am less responsible for a harm if someone else's agency intervenes between my actions and the eventuation the harm. So when we turn to issues of line drawing, we can rely on our understanding of the differences between these kinds of

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[22] Though, admittedly, there is some important literature that aims to question the particular kinds of judgment relied on by deontologist. See, for instance, Greene (2007), but see also, for an important rejoinder Berker (2009). I can't pursue those issues fully here.

[23] For discussion of these views see Parfit (1997). See also Adler (2011) for a defense of incorporating distributive concerns into the cost-benefit framework.

involvement with a harm (or risk) and use that to guide our judgments about, say, how much benefit is needed to off-set doing harm to someone. To that extent, we aren't making "arbitrary" choices that are random or baseless. The judgments can reflect concentrated moral reflection on relevant factors.

Perhaps the concern about arbitrariness is not that our judgments are unguided by reasons but that they might be idiosyncratic. I think we can read Bentham (1823) as raising a concern of this kind for deontological moral theories. Bentham was especially focused on political questions about how to organize the state and even when thinking about private morality he thought the relevant question was what set of publicly acknowledged and shared rules there should be.[24] Each individual, Bentham suggested, will make different judgment calls about where the deontological thresholds should be set. [25] If each acts on her own judgments we will not have the rule of law or of a shared and stable morality, we will have "anarchy". The only alternative says Bentham, is to say that one particular person's judgments should be binding on everyone else, enacted into law and elevated as the public standard of morality. But, this he suggests, would be "despotism" with everyone being objectionably governed in accordance with one individual's peculiar judgments.

As I have emphasized in presenting Bentham's objection, I think this is really a concern that arises when we considering public decisions, especially those made by the state. We are not troubled at all when people make intuitive and idiosyncratic decisions about, say, how to balance the various factors that make one restaurant better than another—ambiance, food, service, and so on—and use those to guide their individual behavior (Cohen 2009, p. 6). We are troubled if crucial decisions about, say, levee design reflect the idiosyncratic moral judgments of particular civil servants or engineers.

What are needed to answer this concern are good *procedures* for bringing together different people's views about which trade-offs are appropriate. For instance, we need to think about which of these would be the most democratic. I have no special proposal about how to do that here—options include more discussion, surveys, voting, and so on—my point is just that these familiar debates about procedure turn out to be highly relevant to implementing deontological theory. And we will also need to consider the appropriate balance between respecting the judgments of experts/officials and those public: a debate that has received a good deal of attention in the context of risk regulation. My fourth response to the concern about arbitrariness, then, is that rather than abandon threshold deontology we should connect questions about threshold choice to broader debates about democracy and the role of the public in risk analysis.

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[24] See Goodin (1995) for a defense of the claim that Bentham was particularly focused on political morality.

[25] Bentham doesn't explicitly speak of thresholds, but his remarks about different balances people will strike between harming, aiding and so on suggest the same issue.

9.6 Conclusions

We have considered whether deontological ethical theories can help guide decision making with respect to natural hazard risks, providing an alternative to the standard cost-benefit approach and consequentialism more generally. It is possible, I hope to have shown, for the deontological framework to be extended to risky contexts, at least if we adopt the threshold version of the view. But trying to apply that framework to natural hazard risks raises a series of difficult questions that need further work. Rather than making a simple distinction between inflicting harms (or risks) and allowing them we need to incorporate a range of different kinds of action that can create responsibility for a harm (or risk), such as making zoning discussions near forests, inviting reliance on construction work or maintenance performed on damns, and so on. This will involve considering how much responsibility is generated by each of these actions, how to divide responsibility where there are multiple agents, and so on. And since these questions are hard and will often involve the use of individual intuition we need to think more about democratic decisions procedures for discussing, collecting, and aggregating our judgments. I think if we can address these questions we will both substantially enrich deontological ethical theory and make some progress towards addressing the difficult practical problems of dealing with natural hazards.

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Chapter 10
Managing Risks of the Unknown

Sven Ove Hansson

Abstract Traditional probabilistic risk assessment needs to be supplemented in at least two ways: We need ways to analyze risks for which no meaningful probability assessments are available, and we need to take into account ethical issues such as voluntariness, intentions, consent and equity. In this contribution three tools for such an extended risk assessment are presented with a particular emphasis on how they can be used to deal with risks that have large components of natural causes: *Possibility analysis* deals with "mere possibility arguments", i.e. risks that we know very little about. The *three-party model* is a framework for analyzing the ethics of risk. *Hypothetical retrospection* is a method for overall assessment of risks in non-numerical terms. These tools are all constructed to introduce important considerations into risk assessment that tend to be excluded or neglected in the traditional approaches. This widening of the scope of risk assessment does not make the assessment easier, but it can contribute to making its output more useful and more responsive to social needs.

10.1 Introduction

The distinction between natural and human-made (or technological) risks is practically useful in many contexts, but no sharp line can be drawn between the two categories. Often one and the same risk is described as natural in some contexts and as technological in others. I was recently in Japan and had the opportunity to take part in discussions about the 2011 tsunami and, in particular, the Fukushima Daiichi nuclear disaster. Some people emphasized that the catastrophe was the outcome of an extremely improbable natural event that it may not have been reasonable to spend large preventive resources on. Others described the events at the power plant as a series of technological failures that could have been avoided with technological and organizational measures such as reliable backup generators and better

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emergency routines.[1] This is not an exception. More often than not, accidents result from combinations of natural and human-made causal factors, and the emphasis may differ between different descriptions of one and the same accident. It is, therefore, advisable to avoid the oversimplified division of accidents into two categories, natural and human-made (Hansson 2003). Instead, we should identify in each case both the natural and the human-made components in the risks and in the measures that we take against them. It is also important to recognize that naturalness does not imply lack of control. There are some "natural" risks that we have efficient means to control and others that we still cannot do very much about (Murphy and Gardoni 2011).

The word "risk" is used in several senses. Often we use it as a generic term, essentially meaning the presence of "an unwanted event which may or may not occur" (Hansson 2007b). On other occasions, it is used as a technical term for a numerical entity that is supposed to be a measure of the degree of severity of a risk, usually its probability or its probability-weighed disvalue. Here I will use the term "risk" in its more general sense.

The risks that we face can be described as a spectrum from the most well-characterized ones for which we can specify both the probabilities and the exact nature of the harmful effects to those that we cannot characterize in either of these respects. In a technical sense, many risks are best described as "uncertainties", i.e. possible future events to which we cannot assign reasonably reliable probabilities. Some of them are even "great uncertainties", by which is meant that we also lack other important specifications such as the nature of the negative effects that they may give rise to. For instance, we know that massive releases of persistent chemicals into the environment may give rise to serious and widespread negative effects on plants and animals, but our knowledge of the possible types of such effects is fragmentary and not at all sufficient for risk assessment. We also know that the evolution of microorganisms or their transmission from non-human species can lead to pandemics that we cannot control. (This is a "natural risk" that is much exacerbated by modern patterns of travel.) However, we are not able to foresee what diseases will be involved in such pandemics. Our lack of knowledge about natural processes has a large role in these and many other cases of great uncertainty.

Standard risk assessment is *reductive* in the sense of reducing the available information on a risk to numbers, thereby making risks of different types comparable. The basic assumption is that the severity of a risk is obtainable as the product of two numerical variables, namely the probability and the severity of the undesired event that the risk refers to (Fig. 10.1). This approach is problematic for at least two fundamental reasons. First, for many of the risks that concern us these numerical values are not available and cannot even be meaningfully estimated. We often have to base our decisions on risks on highly incomplete descriptions. Unfortunately, lack of knowledge about a possible danger does not imply that the danger is small or

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[1] The government-appointed Investigation Committee on the Accident at the Fukushima Nuclear Power Stations (ICANPS) sided with the latter view and described the accident as "man-made" (Tabuchi 2012).

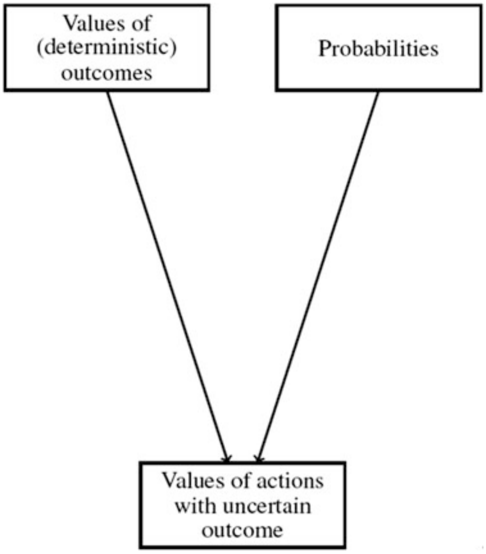

Fig. 10.1 The traditional account of how values of indeterministic outcomes can be derived

that nothing should be done to avert it. (If there ever were any ostriches that buried their heads in sand to avoid danger, they would very soon have been out-competed in the evolutionary struggle.) Secondly, even when these two factors are available, there are many other factors than probabilities and severities that need to be taken into account. Many of these factors can be described as ethical issues since they concern the moral relations among the people involved. In addition to probabilities and severities, we need to take into account intentions, voluntariness, consent, culpability, rights, issues of justice etc. that have usually been neglected in the reductive approach (Hansson 2004c; Gardoni and Murphy 2014) (Fig. 10.2).

Therefore, probabilistic risk assessment needs to be complemented with other methods in order to deal both with those risks that cannot be characterized in the traditional manner and with ethical issues that are not well covered in the traditional probabilistic treatments even when adequate probabilities and severities are available. In this contribution I will introduce three such complementary methods for risk assessment, all of which have been developed within a philosophical tradition of argumentation analysis: possibility analysis that deals with risks that the reductive approach cannot deal with since we know too little about them, the three-party model that provides a framework for analyzing the ethics of risk, and hypothetical retrospection that is a method for overall assessment in non-numerical terms. These methods have all been developed and presented in the context of technological risks. I hope to be able to show that they are equally useful in the assessment of what we call “natural risks”, i.e. risks in which natural causes have a dominant role.

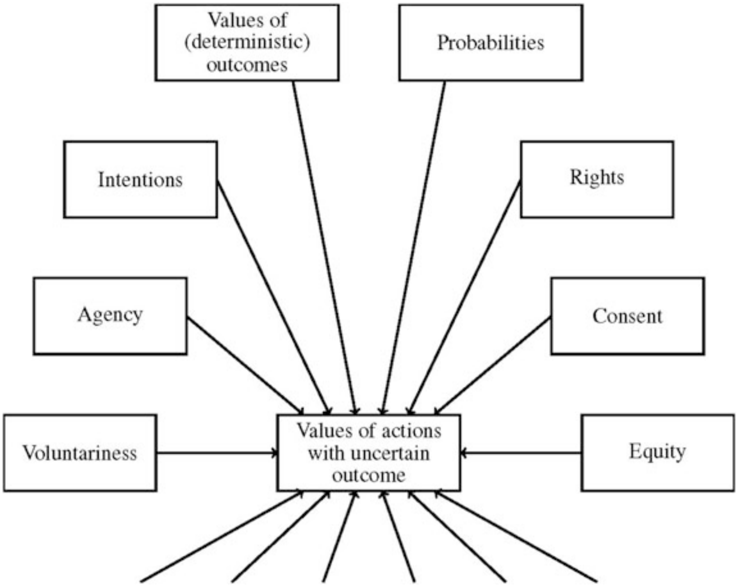

Fig. 10.2 A less incomplete picture of the influences on values of indeterministic options

10.2 Possibility Analysis

10.2.1 Mere Possibility Arguments

When our knowledge is insufficient, discussions often proceed with *mere possibility arguments*, i.e. arguments according to which the mere possibility of some future type of event is taken to have implications for what we should do (Hansson 2004a, 2011). Arguments on mere possibilities can refer to negative consequences ("genetic engineering can lead to unpredictable disasters in nature") or to positive consequences ("nanotechnology will provide us with new molecules that can cure diseases in ways we cannot even imagine today"). They can refer to risks anywhere on the scale between what we consider to be mainly technological risks and what we consider to be mainly natural risks. Possible unknown environmental effects of pesticides exemplify the former and possible new pandemics the latter end of the scale.

It is important to emphasize that the credibility of a mere possibility argument depends on our scientific knowledge. Some such arguments can be set aside for scientific reasons, but others cannot. Sometimes the credibility of a mere possibility argument changes through the development of scientific knowledge. This can be exemplified by mere possibility arguments about genetic modification of organisms. In 1974, eleven American researchers, headed by Paul Berg, wrote a letter to *Science* proposing that scientists should "voluntarily defer" two types of experiments with biologically active recombinant DNA molecules. They did so because there was “serious concern that some of these artificial recombinant DNA molecules could prove biologically hazardous” (Berg et al. 1974).

They had strong reasons for their warning. Given the state of knowledge at the time, the hazards should be carefully evaluated, and a moratorium on the new technology was justified. A careful evaluation was performed, and at the Asilomar Conference on Recombinant DNA in February 1975, the moratorium was ended. Scientists resumed their experiments, applying safeguards that they had agreed upon. Twenty years later Paul Berg (then a Nobel Prize laureate) and Maxine Singer (another leading biologist) wrote a retrospective paper, rightly concluding that the new technology had revolutionized biological science. Moreover, this had been achieved without any of the harmful effects that they had feared 20 years earlier. They wrote:

> Literally millions of experiments, many even inconceivable in 1975, have been carried out in the last 20 years without incident. No documented hazard to public health has been attributable to the applications of recombinant DNA technology. Moreover, the concern of some that moving DNA among species would breach customary breeding barriers and have profound effects on natural evolutionary processes has substantially disappeared as the science revealed that such exchanges occur in nature. (Berg and Singer 1995)

In the 40 years that have passed since the letter in *Science* by Berg and his colleagues, our knowledge in genetics, biochemistry, biology, and ecology has increased dramatically. Experimental procedures that were steps into the unknown in 1974 are now well understood, both chemically and in terms of their effects on the organism. We also have practical experience from a multitude of uses of genetic modification. It has a major role in biomedicine, and about 12 % of the world’s agricultural area is grown with genetically modified crops. Genetic modification is no longer a new and untested technology. The 1974 moratorium was based on a strong mere possibility argument, but that argument cannot be used today since we now have in-depth understanding of the technology, its mechanisms, and the potential positive and negative consequences of its particular applications.

However, although some such uncertainties have been resolved by research, others have remained, such as those concerning possible new pandemics. Furthermore, new uncertainties of the same magnitude have been brought to our attention. For instance, in recent years several proposals have been put forward to solve the climate change problem by various technological manipulations of the natural climate system (climate engineering), such as massive dispersion of reflective aerosols into the stratosphere (Matthews and Caldeira 2007). Even after a thorough investigation of such a proposal, the question remains: Have we identified all the potential risks associated with this technology? Given the global and irreversible nature of some such interventions, the mere possibility that we may have missed some potential risk may be a legitimate argument against employing them (as long as alternative ways to deal with anthropogenic climate change are still available). Another interesting example is biological pest control through the importation of a co-evolved natural enemy of the pest into an area where it is not indigenous. Several failures due to negative impacts on non-target species have led to calls for caution, often based on the mere possibility that an imported new species may have unintended effects on ecosystems (Messing and Wright 2006).

On the other hand, reliance on mere possibility arguments may lead us to refrain unnecessarily from using technologies that would serve us well. For instance, criticism has been voiced against "speculative nanoethics" that focuses on futuristic issues with little or no relevance for actual technology development (Nordmann 2007; Nordmann and Rip 2009; Grunwald 2010). It seems necessary to strike a balance. Mere possibility arguments should neither be rejected offhand nor allowed to block all other considerations. Instead, they must be subject to careful analysis and evaluation. As Nordmann and Rip pointed out, scientific "reality checks" may be necessary. In the following three subsections, three simple intellectual tools for such checks will be introduced.

10.2.2 A Balanced Inventory

An analysis of mere possibility arguments should begin with an effort to identify the various such arguments that may be relevant for the issues at hand. In many cases such arguments are produced profusely by interest groups. However, the arguments that have already been put forward may be the outcome of a biased process in which only arguments in one direction have been included. It is a prerequisite for a balanced and systematic appraisal of mere possibility arguments that such biases are redressed. For instance, if the mere possibility arguments propounded by anti-vaccinationists (such as hypothetical side-effects from polio vaccine) are included in the analysis, then mere possibilities in the other direction (such as a massive polio epidemic infecting most unvaccinated children) will also have to be included.

Therefore it is not sufficient to base our deliberations on the mere possibility arguments that have been put forward spontaneously. A thorough search for such arguments, in support of different standpoints, must be made (for instance with brainstorming methodology). Obviously, a complete list of such arguments cannot be made. However, an initial bias in the selection of mere possibility arguments can be substantially reduced.

In addition to achieving a better balance between arguments in different directions, such an inventory can also contribute to widening the scope of risk assessment. Probabilistic risk analysis has traditionally had a good coverage of impacts that can be treated numerically, such as deaths and economic effects, whereas less easily quantifiable risks such as cultural impoverishment, social isolation, and increased social tensions have often been neglected (Hansson 1989). An inventory of possible effects should not be limited to those that can be quantified.

After an inventory of mere possibility arguments has been made, they should be subject to careful scientific evaluation. Some of them may turn out to be more realistic and specifiable than what was first believed; for instance a worry about unknown toxic effects of a chemical can be substantiated by plausible chemical reaction mechanisms. In other cases, scientific arguments will have the opposite effect. One example is a claim that immunization with an inactivated poliovirus vaccine would cause polio. Based on extensive empirical evidence, such worries should be laid to rest. However, science cannot settle all issues that mere possibility arguments give rise to. To deal with those that science cannot settle we have use for other, more argumentation-oriented forms of analysis.

10.2.3 Symmetry Test

The purpose of symmetry tests is to investigate whether some of the mere possibility arguments can be canceled out by other such arguments. It is, for instance, possible that unique species in a national park will be lost if we do not fight all forest fires efficiently. It is also possible (but perhaps less well known) that species that have adapted to fires will be lost if we fight all forest fires aggressively (Romme and Knight 1981; Turner and Romme 1994). It is possible that nanotechnology will provide us with artificial photosynthesis. But it is also possible that research in other fields that compete with nanotechnology for resources will provide us with that. Two symmetry tests have been proposed in order to search for and evaluate such counteracting effects (Hansson 2004a, 2011).

In the *test of opposite effects* we investigate whether a given mere possibility argument can be countered with an argument showing that we have at least as strong reasons to consider the possibility of some other effect that (1) is opposite in value to the effect originally postulated (i.e. positive if the postulated effect is negative, and vice versa), and (2) has equal or larger moral weight than the postulated effect.[2] If such a contravening possibility can be identified, then the first mere possibility argument has been defeated. We can use the example of forest fires as an example of this. Suppose that someone argues in favor of aggressive firefighting in a particular area since it contains a rich insect fauna, and it appears plausible that a wildfire can lead to the loss of some (unspecified, and possibly unknown) insect species. This is countered by an argument to the effect that some of the tree species may be outcompeted by other, less fire resistant species unless at least some fires are allowed to have their natural course (Hartesveldt 1964). Since the loss of a tree species can be expected to have at least as severe effects on other species, and on biodiversity in general, as the loss of an insect species, this counterargument carries much weight. Under the circumstances given, aggressive fighting of forest fires can have the positive effect of saving some insect species, but also the negative effect of contributing to the loss of tree species. The example also shows that scientific information is often necessary to carry out the test of opposite effects; it is a thought pattern that needs to be filled in with specific argumentation.

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[2] This test was called the “test of alternative effects” in Hansson (2004a).

Importantly, there are also cases in which the test of opposite effects will not defeat the original mere possibility argument. Suppose that a company applies for an emission permit to discharge its chemical waste into an adjacent, previously unpolluted lake. The waste in question has no known ecotoxic effects. A local environmental group opposes the application, claiming that the substance may have some unknown deleterious effect on organisms in the lake. It does not seem possible to construct a positive scenario that can take precedence over this negative scenario. We know from experience that chemicals can harm life in a lake, but we have no correspondingly credible reasons to believe that a chemical can improve the ecological situation in a lake. Therefore, this is a mere possibility argument that resists the test of opposite effects.

In the *test of alternative causes* we investigate whether some given mere possibility argument can be defeated by showing that we have at least as strong reasons to consider the possibility that either the same effect or some other, equally or more undesirable effect may follow if we choose an alternative course of action. For instance, some opponents of nanotechnology have claimed that its development and implementation can give rise to a "nano divide", i.e. growing inequalities between those who have and those who lack access to nanotechnology (Moore 2002). However, an analogous argument can be made for any other new technology with wide application areas. We already have large global "divides" in almost all areas of technology. Under the assumption that other technologies will be developed if we refrain from advancing nanotechnology, other divides will then emerge instead of the nano divide. If this is true, then the nano divide is a non-specific effect that does not pass the test of alternative causes.

In combination, the two symmetry tests can help us prioritize among mere possibility arguments and remove some of them from our considerations.[3] For those that remain, an additional method for priority-setting may be useful.

10.2.4 Prioritization Criteria

The third tool for dealing with mere possibility arguments is to apply three priority criteria that relate to the potential severity of a possible harmful effect: spatiotemporal un-limitedness, interference with complex systems, and novelty (Hansson 1996).

Spatio-temporal limitations reduce the magnitude of potential disasters. The absence of such limitations aggravates uncertainty in many ecological issues. Climate change is the most obvious example. Others are emissions of pollutants

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[3] The procedure is related to Benjamin Franklin's method to deal with complex decisions: Make lists of the arguments in both directions and strike out opposing arguments that have equal weight (Franklin 1970, pp. 437–438).

that spread throughout the whole atmosphere of the globe and the diffusion of chemically stable pesticides that migrate between ecosystems.

Complex systems such as ecosystems and the atmospheric and oceanic systems are known to have reached some type of balance that may be difficult or impossible to restore after a major disturbance. Uncontrolled interference with such systems may have irreversible consequences. The same can be said of uncontrolled interference with economic systems; this is an argument for piecemeal rather than wholesale economic reforms.

Novelty is relevant because we usually know less about new risk factors than old ones. However, in some cases potential risk factors may be less novel than they are thought to be. Interesting examples of this can be found in particle physics. Before new and more powerful particle accelerators were built, physicists have sometimes feared that the new levels of energy might have unknown effects, for instance by starting some type of previously unknown chain reaction with disastrous consequences. Before the start of the Large Hadron Collider at CERN such concerns were disseminated among the public. The decision to regard these fears as groundless was based largely on observations showing that the energy levels in question are no genuine novelties since the earth is already under constant bombardment from outer space of particles with the same and higher energies (Ruthen 1993; Ball 2008; Overbye 2008; Ellis et al. 2008).

10.3 The Three-Party Model for Ethical Risk Assessment

As mentioned above, one of the weaknesses of standard (probabilistic) risk analysis is its limited coverage of ethical issues. The ethics of risk-taking and risk imposition usually concerns problems of agency and interpersonal relationships, including voluntariness, consent, intentionality, and justice, that tend to be neglected in an analysis focusing on the probabilities and severities of outcomes. To deal with these issues, a supplementary ethical analysis, separate from the probabilistic one, can be useful. In this section, the outlines of a model for ethical risk analysis (Hermansson and Hansson 2007)[4] will be summarized, with a particular emphasis on how it can be used for risks with a strong natural component.

10.3.1 The Three Parties

In every risk management problem there are people who are potentially exposed to a risk, and there are people who make decisions that affect the risk. We therefore have to consider the relationships between the *risk-exposed* and the *decision-maker*.

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[4] The model is also extensively discussed in Wolff (2010).

Risks that have been created by humans, such as technological risks, typically also have someone who gains from the risk-taking. This means that a third role, that of a *beneficiary*, is present.

For risks with a dominant natural cause, there is often no beneficiary. No one gains from floods, landslides, or pandemics. But there is in most of these cases another role, namely that of carrying the costs of measures for prevention, rescue and mitigation. Often these costs are largely covered by others than those exposed to the risks. We therefore have, in these cases as well, a three-party system, but the third party is not a beneficiary who gains from the risk but instead someone who faces costs or other disadvantages if we take action to prevent or mitigate the risk. There is no established term that covers this role in all cases. I will use the neologism "counter-affected" to cover persons who are adversely affected in one way or the other of measures taken to reduce the risk. (This terms widens the role of a "beneficiary" referred to in previous descriptions of the three party model.)

As Fig. 10.3 illustrates, the identification of three stakeholder groups gives rise to three binary relations between stakeholders that are in need of ethical investigations. The next three subsections are devoted to a brief discussion of each of these binary relations.

10.3.2 The Risk-Exposed and the Counter-Affected

In some cases the risk-exposed and the counter-affected coincide. One of the clearest examples is risk-taking in medicine. The risks associated with a medical intervention have to be weighed against the potential gains from the intervention. The fact that the same person's interests are in both scales of the balance makes the weighing much less conflict-ridden than in most other branches of risk management (Hansson 2004b). Another important case is risks taken for one's own pleasure (such as bungee-jumping) or when working for oneself (such as climbing without a

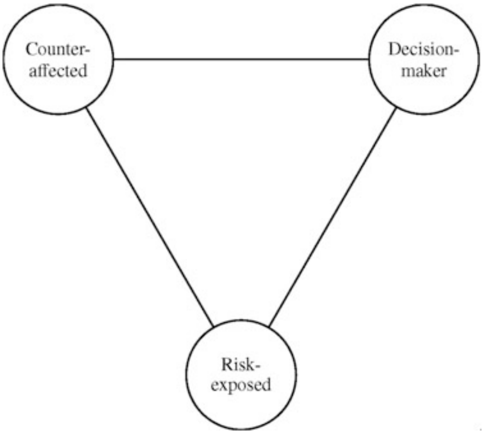

Fig. 10.3 The three-party model of ethical risk assessment

life-line when mending one's own roof). These are all risks that are perceived as comparatively unproblematic in social decision-making.

Controversial technological risks are usually characterized by the risk-exposed and the counter-affected being different persons, i.e. those who receive the largest risk exposure are not the same people as those who receive most of the benefits. Such uneven distributions contribute to making risks socially controversial. People who oppose the siting of an industrial facility or a railroad in their vicinity typically claim that they themselves will carry the risks whereas the owners or users of the facility receive the benefits. This is of course a legitimate ethical concern. It cannot be wiped off with a risk-benefit analysis in which risks and benefits are added up in a total calculus that pays no attention to who receives the risks and who receives the benefits. Instead, differences between the distributions of risk and benefits should be carefully analyzed, and the outcome of that analysis should be the basis of a further discussion on whether or not these differences are compatible with justice (Hansson 2013).

The situation is similar for many risks with a large natural component. Cases in which the risk-exposed and the counter-affected do not coincide tend to be more ethically problematic than those in which they coincide—and very often they do *not* coincide. Justice issues relating to climate change are perhaps the most important example. The populations most at risk are low-income people in developing countries who do not gain much from the activities that give rise to most of the anthropogenic climate change (Okereke 2010).

Obviously, all differences in the social distribution of advantages and disadvantages need not be ethically unjustified. Several well-known types of arguments from moral and political philosophy can be used to support the view that an unequal distribution is, in a particular case, compatible with (and perhaps demanded by) justice. However, this is something that has to be argued. It cannot be assumed without argument that the existing distribution is justifiable.

When a risk is categorized as "natural" it sometimes becomes treated as if no human responsibility is involved. According to some libertarian views, if no human has contributed causally to a danger that you are exposed to, then no human has any moral obligation to help you if the danger materializes. If your means of existence are shattered by a flood or some other extreme weather event, why are the rest of us obligated to help you? A reasoning like this would remove justice from the agenda for natural events.

There are solidaristic counter-arguments against such a libertarian viewpoint, but in most cases it can be refuted already on its own moral terms, since it is based on a false empirical claim. As was noted above, there are almost no purely natural risks. What we call natural risks are events with complex causalities, including both natural and social causal factors. For instance, due to climate change, extreme weather events such as flooding have in part anthropogenic causes (Douglas et al. 2008). It is *factually* untenable to claim that since these events are purely natural, privileged populations in the industrialized countries have no obligations towards third world populations that are affected by them. In today's world, issues of justice are just as relevant for the risks we call natural as they are for those that we call technological.

10.3.3 The Risk-Exposed and the Decision-Makers

The relationships between the decision-makers and those who are exposed to the risk is just as ethically problematic as that between the risk-exposed and the counter-affected. It is essential for an ethical risk assessment to clarify to what extent the risk-exposed have themselves decided on the risk. This is commonly treated as an all-or-nothing issue, and risks are divided into two categories, namely those that are (completely) voluntary respectively (completely) involuntary. However, this is an oversimplification that can sometimes obscure important ethical distinctions. When people are exposed to a risk, this is often the outcome of several decisions that have, directly or indirectly, contributed to the exposure. When a worker is injured through a machine failure, the causal chain includes the worker's own decision to apply for a job in a factory with potentially dangerous machines, the employer's or his representative's decision to buy the machine in question, their further decisions about its use and maintenance, the machine manufacturer's decisions about its construction, etc.

This plurality of human causes usually applies even if natural causes have an important (perhaps dominant) role for the risk. For instance, if people are killed by an unexpected eruption of a volcano, there have usually been political or administrative decisions that made settlements or visits in the area possible, and many of the victims have themselves chosen to be there.

We often prefer single-cause descriptions of events with multiple causality, and these single-cause descriptions tend to have a considerable impact on our moral appraisals. As we have already seen, events with mixed natural and human causes are often described as just "natural", and the classification of an event as natural is then often used as an argument to reject claims of human responsibility. In a similar way, when the risk-exposed person her- or himself has made some of the decisions that led up to the risk, that person is often described as the sole causal agent, and this is used as an argument to absolve everyone else of responsibility. For example, when a smoker dies from smoking, this is the result of a complex combination of causes, including the smoker's decision (many years ago) to smoke her first cigarette, but also many decisions by cigarette manufacturers and others who contribute to the tobacco epidemic. As is well known, the oversimplified description of smoking as a "voluntary" risk, caused exclusively by the victims' own decisions, is systematically exploited in attempts to absolve companies whose business model consists in addicting all of their customers to a product that will kill half of them (Boyle 1997; Hansson 2005).

A tenable ethical analysis has to be based on a nuanced description of the causal structure that goes beyond the usual over-simplified single cause ascriptions to events with a complex causality. Many, perhaps most socially important risks have causes in all three of the categories (i) natural causes, (ii) causes pertaining to the risk-exposed's own decisions or behavior, and (iii) causes pertaining to the decisions or behavior of others than the risk-exposed. We need to see the causes in all three categories in order to be able to discuss ethical aspects of the decision in a well-informed way.

It is also important for the ethical discussion to clarify what information the various decision-makers have access to. In particular, the information available to the risk-exposed is often important for the ethical appraisal. Knowledge is generally recognized as a pre-requisite without which a person cannot act in her own (or anyone else's interest) as a decision-maker. This is the reason why concepts such as a 'right to know' and 'informed consent' are often referred to in discussions about risks and risk-related decision-making (Jasanoff 1988; Sand 2011). A person cannot in most cases be held responsible for taking risks about which she does not have adequate information. Similar arguments apply to acts by which someone exposes other to risk.

It is also necessary to take into account that risks—including so-called natural risks—also affect people who cannot in practice be adequately informed or included in the decision process, in particular minors, mentally handicapped, and temporarily unconscious persons. Exposure of such persons must always be analyzed in an ethical risk assessment. For some risks it may be possible to exempt them from exposure. (In research ethics the standard procedure is to do so.) When their exposure cannot be avoided, it will instead have to be taken into account in the appraisal. In particular, it is grossly misleading to describe risks as "voluntary" when for instance minors are among the risk-imposed. As one example of this, secondary smoking kills about 170,000 children every year (Öberg et al. 2011). Their exposure is not voluntary in any meaningful sense of the word.

10.3.4 The Decision-Makers and the Counter-Affected

The final stakeholder relationship indicated in the diagram concerns the relationship between the decision-makers and the counter-affected persons. The crucial question here is whether the decision-makers benefit from other people's risk-exposure, either directly or indirectly since its continuation will relieve them of abatement costs. Experience shows that decision-makers with such double roles tend to have a low credibility in the eyes of risk-exposed persons and the public in general. This applies to all kinds of risk, irrespective of whether they are classified as natural or not. It is essential to identify such situations. Possible remedies are, of course, to change the decision-making structure by transferring power to an independent body, or alternatively to introduce checks and balances in the form of transparent procedures and independent control.

This finishes my brief presentation of the three-party model. We now have two tools that can help us deal with the risk assessment issues not covered by traditional probabilistic risk analysis. Possibility analysis provides priority-setting criteria for deciding which potential negative effects of decision options we should take into account. The three-party model identifies ethical issues that need to be discussed when risks are assessed and risk management decisions are made. We will now turn to the third tool.

10.4 Hypothetical Retrospection

The third argumentation tool is a simple conceptual tool that can be used to help us in deliberations about what risks, or levels of protection against risks, we are willing to accept. Historically, such decisions have repeatedly been changed, and we can expect them to be changed again. The best that we can achieve is a decision that we can justify and that will be seen in retrospect as reasonable given what we knew and believed at the time of decision.

The tool that I will now present is called *hypothetical retrospection* (Hansson 2007a, 2013). It is a systematized version of an argument pattern that we already know from everyday life. We educate our children to feel into other perspectives than “me now”. We do this in two ways that are illustrated in the following two examples:

> Do not eat all the ice-cream. Think of how sorry Mary will be if there is nothing left for her.
>
> Do not eat all your ice-cream now. Think of how sorry you will be tomorrow if there is nothing left.

In the first example, the child is encouraged to think in terms of another personal perspective than “me”. In the second she is encouraged to consider another temporal perspective than “now”. As every parent knows, both these extensions of the “me now” perspective are parts of what we teach our children in order to help them become responsible and socially well-functioning persons. The first of them, the consideration of other personal perspectives than “me”, has been developed and systematized in many ways by moral philosophers. My claim is that we need to do the same with the second.

The basic idea of hypothetical retrospection is that when we consider making a decision, we should try to predict how we will regard our decision in retrospect. Since we do not know what the future has in store for us this will in most cases require that we consider several alternative scenarios. As a first approximation, we wish to ensure that whatever happens, a later reconsideration will not lead to the conclusion that what we did was wrong. We want our decisions to be morally acceptable (permissible) even if things do not go our way. In order to achieve this as far as possible we need to identify alternative future developments and assess them comparatively.

For a simple example, suppose that two similarly constructed bridges are built, one in Los Angeles and the other in Stockholm, Sweden. A couple of years after they were built, both bridges are severely damaged in major earthquakes. In the Los Angeles case, the decision not to make the bridge earthquake resistant is sure to be criticized after the fact (i.e. in actual retrospection) and will be seen in retrospect as irresponsible. In the Stockholm case, the corresponding decision will probably be seen as an acceptable risk-taking since large earthquakes are considered to be extremely improbable in that area. In a hypothetical retrospection, i.e. when we consider beforehand how we may come to see this in the future, we can expect the same pattern.

The following example from (Hansson 2007a) concerns a somewhat more complicated case: A factory owner has decided to install a fire alarm system in a building that is used only temporarily. When the building is taken out of use, the fire alarm has never been activated. The owner may nevertheless consider the decision to install it to have been right since at the time of the decision other possible developments had to be considered in which the alarm would have been life-saving. This argument can be used not only in actual retrospection but also, in essentially the same way, in hypothetical retrospection before the decision. Similarly, suppose that there is a fire in the building. The owner may then regret that she did not install a much more expensive but highly efficient sprinkler system. In spite of her regret she may consider the decision to have been defensible since when she made it, she had to consider the alternative, much more probable development in which there was no fire, but the cost of the sprinklers would have made other investments impossible. Of course, this argument can be used in hypothetical retrospection just like the previous one. In this way, when we perform hypothetical retrospection from the perspective of a particular branch of future development, we can refer to each of the alternative branches and use it to develop either counterarguments or supportive arguments. In short, in each branch we can refer to all the others.[5]

The aim of hypothetical retrospection is to achieve that whatever happens, the decision will be morally permissible from the perspective of actual retrospection. To achieve this, the decision has to be acceptable from each viewpoint of hypothetical retrospection. What makes this feasible is of course the fact that although each hypothetical retrospection takes a viewpoint in one particular branch of future development, from that viewpoint it deliberates on what one should have done, given the knowledge available at the point in time of the decision, and therefore it also takes into account the need to be prepared for the other branches.

Hypothetical retrospection can be developed for several purposes. It can be developed into a *decision-theoretical criterion* for decisions concerning an uncertain future. As I have discussed in detail elsewhere (Hansson 2007a, 2013) it will then have to be specified in various respects, such as the following:

- Hypothetical retrospections are enacted at some future point in time, in various branches of possible future developments following after the decision. These branches are so selected that for each alternative, the future developments under which it would be most difficult to defend in retrospect will be represented.

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[5] Note that hypothetical retrospection does not lead to a maximin solution. In this example the maximin decision rule would require that the sprinkler system be installed.

- The hypothetical retrospections are based on the moral values that the deliberator has at the time when it is performed (not on predicted future values).
- If there is an alternative that comes out as morally acceptable (permissible) in every hypothetical retrospection, then such an alternative should be chosen. Otherwise, an alternative should be chosen that is optimal in the sense that it does not exceed, in any hypothetical retrospection, the lowest level of unacceptability that some alternative does not exceed in any hypothetical retrospection.[6]

Hypothetical retrospection has also been developed as a *participative procedure* in which people affected by a decision deliberate on how they would react in the future to various possible outcomes (Godman and Hansson 2009; Jebari and Hansson 2013). Finally, hypothetical retrospection can be simplified to a risk manager's *rule of thumb*: "Make a decision that you can defend also if an accident happens."

10.5 Conclusion

I hope to have shown that in the management of natural as well as human-made (or technological) risks we need a variety of intellectual tools that help us to develop and evaluate valid arguments on the comparative advantages of different risk management options. The assessment tools that are currently most in use are reductive in the sense that they tend to reduce our description of options to a very short a list of variables, usually just the two quantifiable variables probability and size of damage. The tools I have proposed do the very opposite; they broaden the scope of considerations in order to cover aspects such as insufficiently characterized consequences (Sect. 10.2), moral issues (Sect. 10.3), and future perspectives on today's decisions (Sect. 10.4). With such tools, we can introduce important considerations into risk assessment that would otherwise be excluded or neglected. Obviously, this widening of the scope may not make risk assessment easier, but it can contribute to making its output more useful and more responsive to social needs.

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[6] Note that this criterion does not coincide with regret avoidance or minimization. Regret is a psychological reaction, not an argued moral standpoint. Our moral aim when planning for the future is not to avoid a particular psychological reaction (that may in many cases be unavoidable). Instead it is to avoid future situations in which it will be our considered judgment that we have done wrong. Such a situations are often accompanied by regret, but it is not regret that we have a moral reason to avoid.

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Chapter 11
Intergenerational Justice in Protective and Resilience Investments with Uncertain Future Preferences and Resources

Louis Anthony (Tony) Cox Jr. and Emeline D. Cox

Abstract How much should each generation invest in building resilient infrastructure to protect against possible future natural disasters? If such disasters are infrequent, members of each generation may be tempted to defer investments in resilience and protective infrastructure (e.g., in building or improving dams and levees; retrofitting office and residential buildings; creating more robust transportation, power, and communications networks; etc.) in favor of consumption or growth. Succumbing to this temptation imposes risks on future generations of needlessly large losses or disproportionate need to invest in resilience. Yet, even the most dutiful and altruistic present generation has limited obligations to invest to protect future ones, especially if present investments in resilience reduce growth and future prosperity, or if the preferences, priorities, resources, and capabilities of future generations are highly uncertain. This paper discusses several different frameworks for clarifying how much each generation should invest in protection. Optimal economic growth models provide a well-developed technical framework for maximizing average or minimal expected social utility over time, but require consistency and cooperation over time that may not be psychologically or politically realistic. If investment decisions are viewed as a form of dynamic "dictator game" in which earlier generations choose how to allocate benefits between themselves and later generations, then insights from behavioral economics, risk psychology, and moral psychology suggest cues related to deservingness and trustworthiness that powerfully affect what is perceived as fair and right in such settings. A Rawlsian concept of justice (what investment decision rules would people choose from behind a veil of ignorance, in which no one knew what generation he or she would be born into?) solves the problems of over-discounting long-delayed and uncertain consequences that have frustrated some previous efforts to apply cost-benefit analysis to ethically charged issues involving intergenerational justice. We suggest several principles for applying insights from these different frameworks to investments in building resilient communities and mitigating natural disaster risks across generations.

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11.1 Introduction: How Much Care Does Each Generation Owe to Future Ones?

Each of us lives with decisions that our former selves have made—choices about what to read and study, whom to marry, where to live, what to work at, how hard to work, how much to consume, and what to do with any savings. Our satisfaction with the choices made by our prior selves may be mixed, but it is not unusual to find that our own current choices are only modestly responsive to the imagined preferences and evaluations of our future selves (Kahneman 2011). And so we may let slide New Year's resolutions that our future selves will predictably wish we had abided by; spend more on current consumption and less on savings or prudent investments or retirement plans than our censorious future selves will, predictably, deem optimal; and succumb to tempting but risky prospects in the heat of the present moment knowing that, with high probability, we will soon regret them as imprudent choices that we will (predictably) wish we had made differently.

Researchers investigating individual preferences and choices over time and under uncertainty have long noted, and created analytic models of, the dynamic inconsistency of individual plans and intentions formed under realistic (hyperbolically discounted) preferences for future rewards (*ibid*). More usefully, they have developed a large array of devices for improving the time-consistency of present decisions to help us make present choices that are less regrettable to our future selves. These devices range from freezing credit cards in block of ice to changing defaults and nudges (e.g., to opt-in or opt-out of an employer-sponsored savings or retirement plans such as Save More Tomorrow) to encouraging "premortem" thinking about how well-intended plans and projects might come to be seen in retrospect as predictable failures. Such imposition of dynamic consistency and rationality constraints and effortful ("System 2") deliberation to restrain and modify the choices urged by immediate intuitive and impulsive ("System 1") responses to the opportunities and temptations before us is at the forefront of current efforts to improve real-world decision-making for individuals by better integrating and coordinating the recommendations from Systems 1 and 2 (Kahneman 2011). It also corresponds to venerable traditions in personal ethics that extol the virtues of temperance, patience, prudence, thrift, steadfastness, and the like.

Social decision-making, too, raises questions of how best to trade-off the needs and preferences of current vs. future agents (Oliver et al. 2014). In many cases, these agents include members of present and future generations, rather than only our own selves at earlier and later dates. Crucial practical risk management policies and social investment decisions depend on how we trade-off their interests. For example,

- How large a tsunami, hurricane, earthquake or other natural disaster should nuclear power plant designers, levee designers, sea wall builders, and other construction and infrastructure engineers design for? Following experiences with extreme events such as the Fukushima tsunami or Hurricane Sandy, it is

common for news stories, editorials, and politicians to urge that more should have been done and should be done now to provide for facilities that would better withstand the stresses of wind and water under such extreme conditions. Hindsight bias may make such criticisms and recommendations inevitable. But should engineers henceforth design for the most extreme events that are expected to occur on average once every 50 years, or 100 years, or 1000 years, or for some other level of extremity? Designing to protect against more extreme (rarer) events typically costs more, but the future risk reduction benefits purchased by these present investments in safety may be very uncertain, depending in part on future climate and weather and perhaps technological advances.
- How much should we invest in developing and stockpiling antibiotics and other countermeasures in case of an anthrax (or other) outbreak? The preventive measures cost money now. Whether they will be used before they expire, and how much good they will do if they are used, are typically quite uncertain. If the decision problem is stationary (i.e., looks the same starting from any point on time), then it may be reduced to a choice between (A) Creating and maintaining some level of stockpiled countermeasures, costing a certain amount per year; or (B) Foregoing the costs and benefits of doing so. In either case, some people alive now and others not yet born may share in the costs, risks, and benefits resulting from whatever decision is made.
- *How much should we spend now in seeking to postpone or mitigate future losses from climate change?* Is it better to commit a substantial fraction of present GDP to climate change mitigation efforts, or to invest in current economic growth and technological and institutional progress, so that future generations will be better equipped to deal with any problems that materialize?
- *How much should we spend per year on nuclear fusion reactor research?* If there is substantial uncertainty about whether and when fusion-generated power production might become practical (e.g., at least producing more power than it consumes), then how much should the current generation invest in fusion R&D? Under what conditions (if any) should it stop investing in favor of more promising alternative uses of current resources? If future generations were allowed to vote on or have input to current decisions, how (if at all) would that change the answers?

These examples, and countless others in the realms of public finance and investments, consumption of non-renewable resources, costly exploration and discovery initiatives, storage of radioactive wastes, and even military investments in long-term security and readiness, illustrate the challenges and importance of learning to address preferences and trade-offs in decisions with consequences that affect multiple generations. All of them can be posed generically as decisions about *how much care (whether measured in prevention, investment, or other expenditures) current decision-makers should take in order to benefit future recipients of the benefits of these decisions*. Making such decisions wisely requires constructive frameworks for determining both *what* we should decide to do now, and *how* we should decide what to do now, given that some of those who bear the consequences may not be alive yet to participate in the decisions.

Optimizing trade-offs between present costs of taking care (or investing in risk reduction) and uncertain future risk-reduction benefits requires an approach to decision-making different from traditional subjective expected utility (SEU)-maximizing decision analysis. The fact that there are multiple stakeholders, not all of whom are alive at present, moves the decision problem from the domain of a single decision-maker to the less well-developed domain of multiple agents, for whom justice and cooperation over time in the absence of opportunities for explicit collaboration and agreement may be important. Even defining clearly what "optimize" means in such settings is difficult. At the individual level, what seems the best choice in retrospect may be very different from what seemed best in prospect, when decisions had to be made and when many possible futures were being considered. In retrospect, evaluations of alternatives can be powerfully affected by hindsight bias, regret, blame-seeking, availability bias, and other potent psychological influences on how we judge previous decisions (Kahneman 2011). In prospect, our evaluations and judgments about what course of action seems best are influenced by different biases, including over-optimism, narrow framing, and over-confidence (*ibid*). Defining a single concept of "optimal" choice that satisfies the biases of both forward-looking and backward-looking evaluations may be impossible. At the group level, what most people prefer to do now may differ predictably from what most of them (or future generations) will later wish had been done now—and from what they may praise or blame current policy makers for doing or failing to do. Such differences can arise because of predictable shifts in beliefs and information, or from changes in tastes and preferences, as well as because of predictable differences in prospective and retrospective preferences and evaluations of alternatives.

The following sections present several frameworks for thinking constructively about how much we should spend now to protect against possible future natural disasters by investing in more resilient infrastructures and communities, precautionary measures, sustainable production and consumption practices and processes, and other instances of costly present care taken to create potential future risk-reducing benefits that will affect multiple generations. To simplify and clarify key issues, we first introduce simple, idealized models of multi-generational conflict and cooperation in the gradual consumption of a desirable resource, generically called "capital stock" or, more colloquially, "pie." This can be variously interpreted to illuminate issues such as savings vs. investment in growth of capital stock in economic growth models; optimal consumption of a scarce resource that many generations would like to share (e.g., oil, or susceptibility of microbial pathogens to current antibiotics, or military reputation with allies and with enemies, etc.); investment in a stock of "safety" in infrastructure (e.g., fraction of bridges replaced or renewed no more than a target number of years ago, or height of a levee or sea wall to protect against flooding during extreme weather events); or investments in precaution against future disasters (e.g., stockpiling of antibiotics or other countermeasures). We consider how one might answer the ethical questions of how big a piece of the remaining pie each successive generation should take, and what duties each generation has to add to the stock of pie or capital, if doing so is possible but costly. This multi-generational sharing of a pie, and generalizations in which the size of the pie can change due to the production and consumption decisions of each generation, and perhaps to random events, provide fruitful metaphors for clarifying both economic and ethical aspects of intergenerational justice that arise in many practical applications, including decisions about how much each generation should spend to help reduce risks from natural disasters for future generations. We compare several principles and constructive analytic and ethical frameworks for deciding what each generation should do, addressing both what decisions should be made and how they should be made. Finally, the main generalizable insights and results from applying these frameworks to problems of intergenerational cooperation and justice are summarized, with attention to how they might be applied to improve practical decisions in which intergenerational consequences and justice are key concerns. In particular, we discuss implications for how to make ethically defensible investments in protecting against natural hazards, as well as implications for proposed principles of sustainable consumption and production of safety benefits.

11.2 Simple Models of Intergenerational Justice: Sharing a Pie Over Time

An idealized model of intergenerational cooperation and decision-making often used in economics, philosophy, and game theory discussions of intergenerational justice is a pie-division problem (e.g., Bahr and Requate 2014; Schmidtz 2011). At the start of the problem, the first generation is endowed with a pie of fixed size, conventionally normalized to be 1, or 100 %. Members of that generation must decide how much of the pie to consume themselves, and how much to leave as a bequest to the next generation. Each successive generation in turn must then decide how much of the endowment of pie that it received from previous generations it will consume, and how much it will pass on to later generations. In the simplest case, the pie does not grow or shrink, except by the consumption decisions of each generation. Of course, generations may overlap, but the simplest models treat them as discrete; this does not substantially affect the analysis.

In variations of the problem, the pie not consumed grows at some rate (analogous to the savings and investment rate in economic growth models); or additions to the stock of pie may occur at random times (analogous to discoveries of new deposits of a non-renewable and valuable resource such as oil); or the pie may be perishable or may randomly shrink or disappear (analogous to depletion or exhaustion of a resource, or to random destruction of property by disasters). In each variation, the key question of how much to consume now remains. For modeling the issues that arise in investing to protect against natural disasters, it is useful to allow two different types of investment for unconsumed pie: (a) Invest in growth (i.e., save some pie, which may then grow at a certain rate); or (b) Invest in safety, which reduces the amount of pie lost when disasters occur.

11.3 Analytic Frameworks for Managing Cooperation Across Generations

This section briefly introduces several different analytic frameworks from economics, game theory, sociology, and philosophy for addressing the question of how much each generation should consume, save, and invest, where investment could be either in growth (as in traditional economic models of optimal consumption and savings/investment over time) or in safety.

11.3.1 Economic Growth Models

For the past century, classical and neoclassical economic models of optimal capital accumulation and growth, such as the Ramsey (1928), Solow (1956), Swan (1956), and Phelps (1961) models, have been used to answer questions about how best to manage a society's consumption, savings, and investment over time. These models describe the changing stock of capital (or "pie") over time by differential equations in continuous time or by difference equations in discrete time, such as

$$K(t+1) = (1+g)(1-c)[1-d(t)]K(t) \tag{11.1}$$

where $K(t)$ is the stock of capital at the start of period t; g is the fractional growth rate for unconsumed capital (typically between about $g = 0.02$ and $g = 0.10$ per year); c is the consumption fraction [and therefore $(1-c)$ is the savings fraction, often denoted by s]; and $d(t)$ is the random fraction of capital lost in period t due to disasters. In classical economics, the capital good, K, is often interpreted as something like "corn" that can be either consumed, thereby producing immediate utility from consumption; or saved and invested ("planted"), in which case it will grow at rate g and expand future opportunities for consumption and savings/investment. In more elaborate models, the values of c and g may also vary over time. Traditional deterministic economic models of optimal consumption, savings, and growth do not model losses from disasters (in effect, assuming that all $d(t) = 0$), but do model labor supply and population growth, in addition to capital growth. Utility in period t is usually assumed to be based on the amount consumed then, $cK(t)$. A central planner who wishes to maximize the net present value of utility (or, in some variations, the steady-state sustainable level of utility) can solve a dynamic optimization problem, constrained by the differential or difference equations for capital accumulation (and for growth in the population and labor force, if they are modeled), to obtain recommended levels of consumption, savings, and investment for each period (Ramsey 1928). Extensions to stochastic growth models, in which the growth rate of unconsumed capital, g, varies randomly over time, have been developed and analyzed using techniques such as stochastic dynamic programming to illuminate the trade-offs between present and future consumption implied by different growth rates (or distributions of growth rates, if they are random) and polices (Olson 2005).

Useful qualitative insights flow from such economic models, which characterize the set of possibilities for intergenerational choices and their probable consequences over time. Models of capital consumption and accumulation specify the physics, or rules of the game, within which intergenerational sharing of resources, consumption, and production take place. They also reveal qualitative properties of optimal policies. For example, analysis of growth models reveals conditions under which all optimal growth trajectories (i.e., sequences of states, consisting of consumption and savings/investment levels in each period, that jointly maximize discounted utility or similar objective functions) approach each other and stay close to each other along most of their lengths, regardless of the initial state. Such optimal growth path "turnpikes" exist for many deterministic and stochastic growth models. In simple models, the optimal policies have simple and intuitively appealing economic interpretations, with each period's consumption and investment being optimized by adjusting consumption levels to equate the marginal utility from further current consumption to the discounted expected marginal value of further investment (i.e., the product of the marginal productivity of investment and the marginal utility from consuming the incremental output next period) (*ibid*).

Perhaps most interestingly, stochastic growth models reveal that there may be a critical threshold level of the initial capital stock above which it is guaranteed (with probability 1) that the optimal policy will never exhaust the capital stock, but below which there is a risk (or, if the growth rate g is variable enough, a certainty) that even optimal management will eventually end with $K = 0$ (collapse). Such results have implications for the management of fisheries and other renewable resources. If extinction is a realistic possibility, then keeping the stock above the threshold needed to avoid extinction might well be an overriding priority, trumping all other considerations about what each generation owes to future ones. Including the possibility of disasters in growth models [$d(t) > 0$] can modify optimal policies, e.g., by providing reason to restrict current consumption to provide an adequate margin of safety. For a non-renewable resource (i.e., growth rate $g = 0$), the optimal policy for sharing the initial stock among generations may shift toward more consumption earlier on if disaster might destroy some or all of the remaining stock. Whether such generalizations hold depends on details of the model considered, such as whether utility of consumption exhibits increasing or decreasing marginal utility (or some of each, perhaps being S-shaped, e.g., if consuming very little oil per generation has zero or little marginal utility compared to consuming more, but consuming a lot also generates less utility per barrel than consuming less). Likewise, incorporating disaster mitigation opportunities into a detailed model requires specifying the cost curve or technology possibilities for spending $K(t)$ to reduce (shift leftward the distribution of) $d(t)$, and how long the effects of such expenditures last. For example, investing in higher sea walls or levees consumes more of the current capital stock that might otherwise have been spent on consumption or invested in economic growth, but reduces the probable losses from floods during the useful life of the walls or levees. Understanding the relation between present costs and future benefits, as modeled by the leftward shift in the loss terms $d(t)$ in future periods purchased by a current investment in safety, provides the essential technical information about possible costs and benefits of disaster risk reduction needed to decide what to do in a multi-period optimization model.

If the model includes population sizes and labor forces, and if a value function for reducing lives lost in the event of a disaster is included in the objective function (thus inviting the usual vexed questions about how to value statistical lives saved), then economic optimization models can deliver recommendations for consumption and investments (in growth and safety) in each period that take into account this evaluation of lives saved. The effects on optimized current consumption of allowing for potential disasters depend on model details; in various specific models, they range from consuming more now ("Get it while it lasts") to consuming less now in order to protect and expand future opportunities ("Safety first," "Make hay while the sun shines," i.e., invest while it is still productive to do so). If the objective function is smooth and exhibits diminishing marginal returns, then optimizing multi-period consumption, investment, and savings (e.g., via stochastic dynamic programming) typically requires equating the marginal returns from incremental expenditures of $K(t)$ on present consumption, on savings and capital growth, and on disaster mitigation, assuming that future decisions will also be made optimally.

For our purposes of comparing different frameworks for making intergenerational consumption, growth, and safety (i.e., disaster mitigation) investment decisions, the point of including the random disaster term $d(t)$ is not to study optimal growth policies in specific models, but only to point out that standard economic methods for studying optimal consumption and investment over time in models of capital and growth can easily be modified to investigate how the possibility of capital-destroying disasters—and of safety investments that mitigate them—changes optimal policies. Overall, the possibility of investing in precautions that stochastically reduce the damage done by disasters (sacrificing some present consumption or investment in growth by instead spending some of $K(t)$ to shift the distribution of $d(t)$ leftward, toward smaller values) provides an alternative to savings and investment as a way to increase capital stock and production and consumption possibilities over time.

In this framework, concerns for intergenerational justice are addressed implicitly, by making decisions in each period, or for each generation, to maximize the objective function (e.g., expected discounted utility) for all. A fundamental limitation of all such models is that no single objective function may correctly represent the preferences of different generations, or even of social planners living at different times. Not only might future tastes and preferences for consumption vs. safety trade-offs and future societal attitudes toward accepting or mitigating disaster risks differ from present ones, but also future generations whose wellbeing is discounted in present objective functions might wish that a different objective function had been optimized. (Worse, if current choices about wealth vs. safety affect the existence or sizes of future generations, then the hypothetical preferences of potential future individuals might be considered to matter in deciding what should be done now. But the hypothetical preferences of as-yet non-existent individuals provides at best a speculative basis for making present choices.) Allowing different generations to have, and to act on, different objective functions from the current generation's requires shifting our analytic perspective from multi-period economic optimization to game-theory to better understand how the choices of different generations interact over time.

11.3.2 Behavioral Game Theory Framework for Strategic Interactions Among Generations

Game-theoretic frameworks for deciding how much of its inherited stock of goods each generation should allocate to consumption and how much it should bequeath to its successors via investments in disaster mitigation measures and economic growth differ radically from optimal economic growth models (D'Albis and Ambech 2010; Balbus and Nowak 2008). They drop the fiction of a single dispassionate social planner who is willing and able to make decisions for each generation to maximize some overall objective function. The difference can be illustrated as follows. Suppose that the first generation, perhaps motivated by compassion or ethical considerations, intends to consume only a small share of the initial endowment of a non-renewable resource ("pie"), leaving the rest for posterity. If they somehow learned that the second generation plans to consume the entire remainder, passing nothing on, then generation 1 might be inclined to revise its initial generous intent, consuming more itself. But, if it turns out that generation 2's intent to consume everything is based on discovering that generation 3 plans to consume whatever is bequeathed to it, passing nothing on, then generation 1 might feel that generation 2 is not so undeserving after all. In short, what each generation concludes that it should do might well depend on what it expects subsequent generations to do. If a generation trusts that a plan that it initiates for enriching the future will be followed faithfully by at least the next few generations, then it may bequeath more than if it lacks such trust.

How such trust arises is better illuminated by behavioral game theory, experimental economics, psychology, and descriptions of what is sometimes called "social capital" (trustworthiness of others with whom one participates in dealings) than by the logical prescriptions of formal game theory models, in which trust plays no role. Real people are often far more altruistic and cooperative than models of purely rational behaviors and interactions predict or explain. For example, in the much-studied dictator game, one player is given an amount of money (or other desirable good) to divide between himself and a second player. The recipient has all the power in this game, and might be expected to keep everything for himself. But this is not what is observed in many experimental dictator games and variations (e.g., Bahr and Requate 2014): most dictators choose to bequeath substantial shares (e.g., 20 % or more) of the initial endowment to the other, powerless players, depending on what social norms are evoked by the contextual cues of the experiment, such as earning, sharing, pure giving, etc. (List 2007). To what extent generous sharing is observed in practice depends on many contextual factors, such as whether participants view their interactions in a market frame or in a gift frame; on whether taking as well as giving is included in the feasible set of actions; on whether the player selected as the dictator believes that the choice reflects his own skill or luck in a fair contest; on how often the situation is repeated. But purely selfish behavior is seldom observed (List 2007). The multi-generation division of an initial endowment can be viewed as an expansion and generalization of the dictator game in which each generation is in the position of the dictator in deciding how much to share with powerless future generations.

Although behavioral game theory and experiments provides insights into realistic behaviors that formal non-cooperative game theory (e.g., based on the understanding that all rational players will use sub-game perfect equilibrium (SPE) strategies if they exist and are unique) cannot, neither type of analysis is concerned primarily with clarifying what choices are most morally correct. Behavioral game theory and behavioral economics recognize that people (and some other primates) have intuitive and emotional responses to perceived fairness, equity, injustice, reciprocity, and altruism that are important drivers of decisions about when and how much to share in a variety of settings, including the dictator game and its variants. These personal moral intuitions and impulses are tremendously important in helping real people to cooperate more successfully than purely rational (SPE-implementing) agents can in many situations (e.g., one-shot and iterated Prisoner's Dilemma, the stag game, the centipede game, the trust game, and other staples of modern game theory) (Haidt 2012). Yet, they do not provide a coherent normative account of applied social or moral decision-making that can be used to obtain reliable moral guidance on important policy questions, such as how best to share the burdens and benefits of investments in disaster mitigation and in economic growth across generations. To the contrary, our moral intuitions are easily dumbfounded when situations appeal to several competing moral intuitions (Haidt 2012), as in alternative framings of tax breaks for dependents as providing disproportionate benefits to the wealthy, if they are used; or as imposing disproportionate costs on the wealthy, if they are not (Kahneman 2011). Likewise, the prescriptions from formal mathematical non-cooperative game theory models of interacting rational players (or generations, in our setting) are not intended to convey any moral authority: SPE solutions and refinements only guarantee that no player can get more of what it wants by changing its strategy, not that what any player wants is morally worthwhile.

11.3.3 Axiomatic Solution Concepts from Cooperative Game Theory

A different branch of game theory concerns itself directly with normative principles that participants in a cooperative enterprise might adopt to decide how to share the benefits from cooperation. This is axiomatic game theory, which defines and studies the logical relations among solution concepts in cooperative games, such as those involving bargaining or fair division of one or more goods. For example, the Shapley value, which assigns to each player the expected incremental value that the player creates by joining a coalition of other players (when the order in which the players join is random), is the unique way to allocate gains from cooperation that satisfies certain axioms, such as that players be treated symmetrically, without favoritism (each player's allocation depends only on what it contributes, and not on who the player is) and that the allocation procedure should be Pareto-efficient, allocating 100 % of the potential gains from cooperation. The Nash Bargaining solution, which maximizes the product of the utility gains of the players compared to the no-agreement outcome, is likewise the unique solution concept satisfying these two conditions and an additional two (that the outcome should not depend on the arbitrary choice of scales for expressing player utilities, and that expanding the opportunity set of utilities jointly available to the players by introducing new options should either leave the original outcome unchanged, or change it to one of the newly added options). Each of these and many other proposed solution concepts for sharing in the cooperative production and allocation of desired outcomes, can be justified as the unique concept implied by a set of more-or-less reasonable-seeming normative axioms, many of which directly represent principles of fairness such as symmetry (i.e., no favoritism), or maximizing the minimum payoff among players, as well as Pareto efficiency.

However, axiomatic cooperative game theory is vulnerable to its own version of moral dumbfounding: different proposed normative principles can conflict logically. This leads to impossibility theorems showing that no possible decision procedure can satisfy all the appealing principles (normative axioms) that one might want to require. For example, the Shapley value solution and the Nash Bargaining solution can prescribe different outcomes for the same situation, so that no outcome satisfies the normative principles proposed for both. In such cases, one might try to decide which principles should be sacrificed so that other (mutually consistent) ones can be preserved, or, equivalently, choose among alternative solution concepts. But there is no meta-ethical framework within axiomatic game theory to prescribe or justify which normative principles to keep and which to abandon when there are logical conflicts among them. Axiomatic theories may also under-determine outcomes in practice. For example, the Nash bargaining solution requires knowing what the disagreement outcome is, but it is not always clear how it should be determined, e.g., as the present *status quo*, which may incorporate the results of many historical injustices, or as an idealized initial position that treats all participants symmetrically.

Such questions about how one should, even in principle, implement the prescriptions of normative axiomatic solution concepts, open a gap between their mathematical implications and the information needed to act on them. Theories of justice developed by Rawls and his successors can help to close this gap by specifying a particular initial position from which (idealized, hypothetical) deliberation and selection of principles proceeds. They also provide a meta-ethical framework for reasoning about how societies should choose among rival normative principles (e.g., among different axiomatic cooperative game-theoretic solution concepts) to guide their subsequent applied choices and the rights, duties, and principles of fair distribution or redistribution over time that they should impose on themselves and on each other. These theories are explained next.

11.3.4 Intergenerational Justice

Philosophical discussions of intergenerational justice since Rawls (2001) have considered an idealized form of social contracting across generations. Participants from all generations are imagined to jointly agree on policies for sharing resources and investments over time, such as social savings rates, from a hypothetical "original position" behind a "veil of ignorance," in which no participant knows which generation (or other position within society) he or she will be born into (e.g., Meyer 2009; Manzini et al. 2010). Principles that would be agreed to from behind this veil of ignorance are defined as principles of justice, to which real policy-makers should adhere if they wish to make just decisions. This concept can be applied to inform each generation's consumption and investment decisions, including decisions about how much to consume and how much to invest in disaster mitigation and community resilience, or directly in economic growth, at different times. In the simple case of sharing a non-renewable resource ("pie") over time for a finite number of generations (which may be random, if the duration of the human race is uncertain), the allocation of the resource across generations recommended by such a Rawlsian criterion typically coincides with the allocation that would be achieved by social utility maximization in growth economics, although the two criteria of social utility maximization and Rawlsian justice may recommend different allocations of the resource across generations if the resource can be produced, thereby augmenting its supply, by generations that choose to do so (Llavadora et al. 2010).

Identifying just policies as those that would result from social contracting if all stakeholders started from a symmetric original position solves the problem of having earlier generations exploit their asymmetrically powerful position to the detriment of later generations, e.g., by consuming all of the initial stock of pie immediately. Because participants in the multi-generation social contract arrived at from the original position do not know which generation they will occupy, they are motivated to treat all generations fairly. This framework for inter-temporal justice also provides an alternative to discounting, thus avoiding the ethical problem posed by conventional discounting in cost-benefit analysis of under-weighting the costs and benefits borne by far-future generations compared to those borne by present or near-future generations (van Liederkerke 2004; Parfit 1984). From the original position, the interests of different generations are valued equally, and so any discounting would reflect only real asymmetries, such as in production opportunities (e.g., earlier investments in growth pay off over more years), and not a bias against later generations.

Other proposed features of intergenerational justice have been erected on these foundations by speculating about what people in the original position would agree to. Rawls himself argued that the primary duty of each generation is to bequeath just institutions to the next; once this has been fulfilled (via an "accumulation phase"), a frequently proposed secondary duty is that each generation should pass on to the next an endowment at least equivalent (in size or productivity) to the one it received, so that no generation's consumption reduces the opportunities or wellbeing of those that follow (e.g., Hamilton 1995). However, such proposed principles of *sustainability* in consumption and production invite scrutiny and skepticism (e.g., Wolf 2007), especially if they are asserted without careful qualification and reference to specific underlying economic growth models. For example, in the case of an initial endowment of pie that can only be consumed, and not produced, requiring that no generation's consumption should diminish the stock bequeathed to future generations would imply that none of the pie would ever be consumed—a Pareto-inefficient outcome that would not necessarily appeal to anyone, even behind the veil of ignorance. Similarly, for a model of multi-generational sharing of a renewable resource, Krautkraemer and Batina (1999) show that imposing a sustainability constraint of non-decreasing utility over time creates Pareto-inefficient stockpiling of the resource: everyone would prefer a usage pattern that allowed later generations to have lower utilities than earlier ones. Such conflicts between various proposed criteria for sustainability and what all members of all generations would prefer arise in many other models of intergenerational sharing (e.g., Hoberg and Baumgärtner 2011), although not in all if there is no uncertainty and if property rights, taxes, and transfer payments among generations are dexterously deployed to allow earlier generations to, in effect, purchase resource usage rights from later ones (Howarth and Norgaard 1990). But the frequent conflicts between sustainability principles and economic efficiency (e.g., what is unanimously preferred by all members of all generations) are perhaps unsurprising from a Rawlsian perspective on distributive justice, insofar as social contracting from an original position in which no participant knows what generation he or she will occupy removes any reason to favor the utility or opportunities of later generations over those of earlier ones.

Despite their considerable intellectual appeal, theories of intergenerational justice based on implicit social contracting behind a veil of ignorance are not free of philosophical and logical difficulties. For example, in such theories, it is not always clear how potential future people whose very existence may be affected by present production and consumption decisions should be treated (Meyer 2009). Llavadora et al. (2010) present models in which the possible extinction of humanity is considered as a key uncertainty about the future. They prove that it is optimal, in economic growth models with a policy objective of maximizing the minimum welfare across generations, weighted by the sizes of future populations (so that potential individuals, rather than entire discrete generations, are treated as the participants in the social contract) to ignore this uncertainty about continued survival in deciding how best to allocate consumption and investment over time. This result holds when the economy is sufficiently productive. In effect, the appropriate discount rate due to uncertainty about continued existence is then zero.

Likewise, if future people will have habits, expectations, and preferences that are shaped in part by current production and consumption decisions, then it may not be clear what preferences should be assumed in modeling what they would agree to in the original position. For example, if early generations derive high utility from consumption, and if later generations regard consumption as an unattractive materialistic addiction that thankfully became obsolete when excessive consumption triggered a collapse, then a Rawlsian social contract that allowed members of different generations to bring these preferences with them behind the veil of ignorance might lead to the conclusion that high early consumption is justified. (We acknowledge that it is not clear whether a preference for increasing or decreasing consumption over time can be appropriately debated behind the veil of ignorance, as it may require more preference information than ignorance allows.) But if more gradual consumption would lead to all generations putting a high value on it, then these different assumed preferences might imply that gradual consumption was the just pattern. If each alternative choice about patterns of production, consumption, and investment over time induces the generation-specific preferences needed to justify it (by making it the alternative that would be selected from the original position), then the original position loses its prescriptive power.

11.3.5 Sustainability, Protective Principles, and Fundamental Trade-Offs

Sustainability principles, usually requiring that resources or opportunities or utilities be non-decreasing over time (Hamilton 1995; Wolf 2007), are intended to make sure that current policies do not unjustly sacrifice the interests of powerless future generations in favor of the interests of present generations who currently have the power to make choices. Other approaches have the same goal of protecting the interests of future generations in current decision-making; these range from variations on Rawls's idealized social contracting (subordinating the difference principle, which implies accumulation would never begin if the first generation is also the least well-of, to the desirability of an "accumulation phase") (van Liederkerke 2004) to idealized Nash bargaining solutions in which each generation is assumed to be given the power to veto plans that it considers unacceptable (Manzini et al. 2010). In addition, some optimal growth models imply a sustainability condition, in which, in steady state, each generation passes on to the next the capital that it received from its predecessor, and this stock is maintained at a level that maximizes the utility from consumption per capita for members of each generation (Phelps 1961).

However, when realistic uncertainties about future preferences and choice sets and about the consequences of current decisions are taken into account, the capacity of current decision-makers to protect the interests of future generations effectively may be very limited. For example, Krysiak and Collado (2009) present models in which there is a trade-off between taking actions to protect future generations against risks and taking actions that all generations prefer, while Hoberg and Baumgärtner (2011) demonstrate similar trade-offs between sustainability and efficiency when irreversible policy decisions are made by earlier generations, trying to protect the interests of later ones, but later generations have better information about the (perhaps unforeseen and unintended) consequences of earlier policies.

More generally, sustainable production and consumption, economic efficiency (i.e., Pareto optimality), Rawlsian justice, and free democratic (non-dictatorial) choice procedures have all been proposed as desirable principles for guiding and constraining how societies should make decisions, both within and across generations. But careful analysis indicates that any two of these principles, when appropriately formalized for specific models relating choices to economic growth, can conflict. For example, free democratic choice procedures may lead to outcomes that no one favors, e.g., if different people have different beliefs about the probable consequences of alternative choices, and these probabilistic beliefs are used to help select policies (Nehring 2005). Similarly, conflicts between sustainability criteria and Pareto-efficiency (Wolf 2007; Hoberg and Baumgärtner 2011) and trade-offs between Pareto-efficiency and various measures of intergenerational equity or justice in resource allocations arise for many intergenerational decision processes (e.g., Krysiak and Collado 2009). No matter how well intended, efforts to protect the interests of future generation using the information available today risks creating outcomes that, in retrospect, no one favors; this is especially likely if today's choices have uncertain, irreversible consequences and if future preferences are uncertain (Hoberg and Baumgärtner 2011). Thus, fundamental tradeoffs must be made among these proposed desirable characteristics of collective choice procedures for managing investments in growth vs. protective measures and production and consumption of limited resources (including infrastructures that reduce the adverse impacts of natural disasters) over time and generations. Equivalently, impossibility theorems expressing the logical incompatibility of different sets of principles under stated conditions limit the possibilities for a satisfactory approach to intergenerational cooperation, including management of natural disaster risks.

11.3.6 Investing in Building Resilient Communities and Societies: An Emerging Framework

If the normative frameworks and principles for intergenerational justice we have considered so far—growth economics, behavioral game theory, axiomatic solution concepts for cooperative games, philosophical theories of intergenerational justice, and proposed principles of sustainability and protection of the interests of future generation—all lead to contradictions or unresolved difficulties, then what type of analysis might be used instead to provide practical guidance on how much to spend on consumption, investments in disaster mitigation, and investments in economic growth in each period? One emerging approach avoids such mathematical and theoretical arguments, instead emphasizing building the capacity of communities and societies to respond quickly and competently to new information and circumstances as they arise. This is the framework of *resilience* for communities and societies; it is still under development by many investigators (Bretherton and Ride 2011; Lucini 2014; Tierney 2013). Key concepts are that resilient communities should prepare to manage disasters effectively by accumulating the physical and social capitals needed to adapt and respond effectively and to manage mitigation and recovery efforts when needed. Physical capitals include transportation, telecommunications, power, and emergency medical infrastructures. Social capitals include training and preparation, ability of communities to organize effectively and act competently and autonomously when needed, self-reliant communities, and high trust and individual trustworthiness in cooperating to respond to disasters. Proponents of resilience often argue that communities and societies benefit in multiple ways from developing the capacity, responsibility, and self-reliance needed to improvise and take appropriate actions to deal with possibly unforeseen events. From this perspective, the obligation of each generation to the next may be viewed as bequeathing at least a minimal level of resilience, including the needed physical and social capitals.

Resilience frameworks are still a work in progress. They are sometimes conflated with proposed principles of sustainability, participatory decision-making, environmental justice, environmentalism, putative rights to safety and prosperity, and intergenerational equity for managing interlinked social-economic-ecological systems, often with little explicit discussion of the limitations, trade-offs, and contradictions among the principles espoused. Even without such overlays, however, it is useful to keep in mind the basic idea that investment in building community resilience may be a valuable alternative or complement to investments in economic growth or direct protective measures (e.g., better levees) when the possibility of occasional disasters is present.

11.4 Discussions: Principles for Applying the Frameworks to Improve Decisions and Policies

How might an engineer, planner, or policy maker apply insights from the preceding frameworks to improve practical disaster protection and mitigation decisions, such as how high to build a costly levee or sea wall, or how large (and rare) a tsunami, earthquake, flood, or hurricane to plan for in the design of nuclear power plants or other facilities, or how much to invest in a proposed community resilience or civil defense program? The following suggested principles seek to distil from the frameworks considered above implications to help guide practical decision-making when current choices have long-lasting consequences that may affect risks and benefits to future generations.

1. **Use wide framing**: Consider a wide range of alternatives to optimize benefits produced for resources spent, taking into account opportunity costs. Exploit different ways to reduce risk. The optimal economic growth framework implies that each method for maximizing a social objective function—whether by investing in economic growth, in reducing potential disaster-related losses, in less costly and more rapid and resilient recovery following disasters, or in other improvements that reduce risk or increase wellbeing—should be funded optimally in each period in competition and combination with the other approaches. In simple settings with diminishing marginal returns, for example, this typically requires funding each alternative up to the point where a different one starts to yield larger marginal returns in improving the objective function. Thus, a planner wondering whether to invest in a taller sea wall or barrier against flooding should ask not only "Is the extra cost of a taller barrier justified by the extra benefit from reduced risk?" but also "Could a larger reduction in risk (or, more generally increase in objective function) be achieved by not making it taller, and instead applying the resulting cost savings to other opportunities, such as relocating people or improving local early warning and transportation systems?" More generally, optimal provision of safety and other good requires considering opportunity costs and optimizing economic trade-offs, while avoiding narrow framing (Kahneman 2011) that considers only one approach at a time (e.g., investment in levees, but not change in zoning or land use). The optimization problems to be solved can be viewed as allocating each period's limited resources to a portfolio of alternative ways to increase the objective function, with one of those ways being to bequeath more to the next generation, which may have different opportunities.
2. **Follow golden-rule consumption and investment principles**: Do not over-invest (or under-invest) in protecting or benefitting future generations compared to the present one. Biases such as the affect heuristic, which judges alternatives and shapes perceptions of their attributes and desirability based on whether they elicit positive or negative emotional responses ("gut reactions") (Kahneman 2011) can encourage simplistic thinking that equates current consumption with

selfishness and greed (bad affect) and equates current investment to protect or benefit future generations with benevolence, virtuous self-restraint, and generosity (good affect). Optimal growth models, including ones with ethical and justice constraints, tell a more nuanced story. Under-consumption and over-accumulation of capital stocks to pass on to the future violate the golden-rule maxim of doing in each generation what one would want other generations to do to maximize sustainable utility (Phelps 1961). From this perspective, increasing saving and investment on behalf of the future is not necessarily always better. Instead, saving and investing at the golden-rule rate, and not more, maximizes the wellbeing of present and future generations. Thus, optimal economic growth theory weans us from a multi-generation zero-sum perspective, in which increased current consumption necessarily comes at a cost to future generations. Instead, it encourages a cooperative perspective in which members of different generations collaborate in maximizing the sustainable level of wellbeing.

3. **Use simple rules to help optimize current decisions**: Exploit qualitative properties of optimal policies to simplify practical decisions. The economic growth perspective can be implemented in detail if trustworthy mathematical or computational models are available representing the causal relation between choices and the probabilities of their consequences (immediate and delayed). Techniques such as stochastic dynamic programming can then be used to decide what to do in each period to maximize a social objective function. Mathematical and computational techniques and resulting solutions can become quite sophisticated and complex, but, in many settings, the optimal solutions have qualitative properties that can inform and improve practical decision-making with simple rules that take into account future effects, even when detailed models and numerical optimization results are not available. For example, both optimal growth and Rawslian justice might require first boosting economic productivity as quickly as possible to a level where desirable institutions can be sustained and passed on from one generation to the next. Once there, optimal growth policies often have simple characteristics, such as saving and investing just enough so that the marginal productivity of additional capital stock offsets (equals) its effective depreciation rate due to aging, population growth (which dilutes the capital-per-worker), and other causes, including occasional disasters or catastrophes (Phelps 1961). Risk management to jointly optimize consumption and investments in growth, disaster prevention and mitigation to maximize average utility of consumption per capita per period might require keeping capital stocks of renewable resources at or above certain threshold levels to avoid risk of collapse, which could reduce or eliminate their availability to subsequent generations (Olson 2005). Such simple characterizations of optimal growth and risk management policies can help to focus practical policy-making analysis and deliberation on a few key questions, such as whether the current savings and investment rate is clearly above or below the socially optimal rate [e.g., the golden rule rate, in a Solow growth model (Phelps 1961)]; or whether stocks of renewable resources are currently above or below safety-stock thresholds. The answers then suggest directions for remedial actions, such as increasing or

reducing investment, respectively. Pragmatic constraints may limit how much adjustment can be made how quickly. In short, knowledge of the qualitative properties of optimal policies, such as the existence of thresholds or of optimal rates of capital accumulation or investment, can produce simple decision rules (e.g., take action to increase investment or stock of a renewable resource if we are below the optimal level, or to decrease it if we are above the optimal level, where the optimal level is estimated from data on depreciation rates or renewal rates, respectively). Such simple rules can often help to answer the practical policy question of what to do next, even without explicit formulation, estimation, and solution of sophisticated multi-period optimization models.

4. **Do not discount the utility from future benefits**: Count lives saved in different generations equally and count utility received in different generations equally. In particular, do not discount future lives saved or future utility from benefits received simply because they are in the future. This follows from Rawlsian justice models that treat the interests of future participants in an extended multi-generational social contract symmetrically with present ones. It implies that benefits such as improvements in quality-of-life per person per year due to increased resilience and reduced anxiety, or greater consumption utility per capita-year, should not be discounted. In making cost-benefit comparisons, lives saved or life-years improved that accrue over the lifetime of a facility should all be counted equally according to such models of justice over time. The practical effect of this recommendation is to increase the present evaluation of benefits that flow from current decisions into the future, such as the benefits from risk reductions obtained via current investments in levees or in other protective or resilient infrastructure. Although multi-period optimization methods such as stochastic dynamic programming can still be used to decide what to do in detail, if credible models are available to support the required calculations, concern for intergenerational justice will modify the usual objective function of expected discounted social utility to give equal weights to life-saving or other intrinsically valued benefits received at different times.
5. **Consider the value of waiting**: Do not commit prematurely to expensive present actions with long-lasting or irreversible consequences. Trust future generations to help decide what is best. This principle requires current decision-makers to consider the potential value of seeking and using better information to improve decisions before committing resources or foreclosing other options. For example, it may be worthwhile for Federal regulators to let individual states experiment with new measures first, and to learn from the consequences, before deciding on a Federal policy that all states must follow. This cautious principle, of seeking to learn more before betting large-scale investment decisions with lasting consequences on what currently seems to be the best choice, follows from studies of fundamental trade-offs in making protective investments under uncertainty, such as the trade-off between investing in proposed measures to protect future generations against possible future harms vs. investing in other ways that, in retrospect, all members of all generations might prefer (Krysiak and Collado 2009; Hoberg and Baumgärtner

2011). Acknowledging realistic uncertainties about future costs, benefits, risk attitudes, preferences, technology alternatives, and opportunity costs highlights the potential value of seeking more information before committing to decisions with long-lasting or irreversible consequences, such as about the height of a levee, enactment of enduring regulation of carbon dioxide emissions, diminishment of economic growth rates in order to invest in protective measures, or consumption of non-renewable resources.

Our first principle above, wide framing, encourages planners confronted with a proposed costly measure to reduce risks to future generations to ask not only "*Is it worthwhile?*" in the sense that the proposed measure's benefits exceed its costs, but also "*Is there a cheaper way to achieve the same benefits?*" The latter question is typically a matter for engineers and economists. The answer is often that no one knows yet. If further research can reduce current uncertainties, then value-of-information (VOI) calculations from decision analysis can address the question of whether the benefits of that research, in terms of improving decisions and their probable outcomes, exceed the costs of doing it, including potential costs from delay. (Indeed, such VOI considerations are automatically included in stochastic dynamic programming whenever acquiring more information is a possible choice.) Thus, the planner should also ask a third question: "*Is it worthwhile to pay for better information before deciding whether to approve the proposed risk-reducing measure?*" When decisions have long-lasting consequences that affect future generations, the value of information acquired to help make the best decision—the decision that will be preferred in retrospect when future information becomes available—may be especially great.

Likewise, there may be a value to keeping options open, recognizing that the best choice based on current information may not still be seen as the best one when evaluated using future information. There can be a "real option" value to keeping options open until better information is available on which to act, even if delay is costly. Again, stochastic dynamic programming considers such real option values as well as VOI, and optimizes information collection and the timing of decisions, including ones with irreversible or long-lasting. However, the guiding principle of stochastic dynamic programming is the Bellman optimality principle: that each generation's (or period's) decisions are made optimally, *assuming* that all future generations' (or periods') decisions will likewise be made optimally (Olson 2005). Practical application of this principle across generations requires decision-makers in different generations to collaborate in implementing it consistently, with each generation acting accordingly, but having to trust other generations to do the same. Behavioral game theory suggests that such cooperation is far more likely than would be expected based on purely rational (System 2) responses, in part because of moral psychology and pro-social impulses (System 1 responses) (Haidt 2012) that make us eager to reciprocate the generosity of earlier generations by being, in our turn, equally generous to our successors. However, System 1 responses are notoriously non-quantitative, and are not designed to identify and optimize quantitative trade-offs (Kahneman 2011). Thus, deliberate investments in social capital, a culture of trustworthiness and effective cooperation, and building resilient communities, may help generations to collaborate more effectively over time in implementing long-term plans that benefit all of them.

11.5 Conclusions

Making decisions well over time is challenging for societies as well as for individuals. Deciding how best to allocate current resources to competing ends, of which protection of future generations against natural disasters is one, requires considering what future generations are likely to do to maintain and expand (or, perhaps, to draw down without replenishing) the stocks of infrastructure, social and economic capitals, and other protective investments bequeathed to them. Our moral intuitions often deliver altruistic and benign impulses toward others, including strangers separated from us in time or by geography. But they usually do not render finely calculated decisions about how to optimize trade-offs between our benefits and theirs. Nor do they identify the most efficient use of protective and other investments (e.g., in growth of economic prosperity, or in building community resilience) to accomplish desired trade-offs, or to carry out the prescriptions of ethical and justice theories to maximize the average or minimum wellbeing of members of present and future generations. Methods of multi-period optimization that have long been used in optimal economic growth models can accomplish these quantitative trade-off and optimization tasks. They can be adjusted to incorporate principles of intergenerational justice, such as assuring that the lives and utilities of future people are not discounted relative to those of people now living. In simple models, including the multi-generation pie-sharing example that we started with and in golden-rule optimal growth models (Phelps 1961), multi-period optimization leads to simple consumption and investment rules that also satisfy equity and sustainability conditions. In this way, System 2 methods can be used to help identify multi-generation investment plans to achieve ethical goals that System 1 might approve of. The results can often be expressed as simple decision rules that are useful for informing practical policy-making, such as taking actions to adjust levels of investments or of renewable resources toward desired target levels based on estimated marginal rates of return or renewal rates, respectively, perhaps with adjustments for the value of information and of keeping options open.

However, even when clear and simple rules can be identified for maximizing a social objective function, such as the average or minimum utility per capita in present and future generations, it takes cooperation across generations to implement them. In turn, this may require just and effective institutions, high social capital, and community resilience, as prerequisites for effective multi-generational cooperation in managing losses due to natural disasters or other causes. These insights suggest that successful efforts to improve intergenerational justice and efficiency must be rooted in a deep understanding of human social nature and cooperation over time, and of the possibilities for designing and maintaining effective cultures and institutions for promoting and sustaining such cooperation. They also require clear understanding of the goals that we seek to achieve in collaboration with other generations, and of the trade-offs that we want to make when those goals conflict.

The frameworks and principles we have discussed make a start at clarifying possible goals and trade-offs among them, and the implications of technical principles (especially, stochastic dynamic programming distributed over multiple generations) for achieving them. How to develop institutions and cultures that promote effective cooperation over time and across generations, as well as within them, without necessarily assuming that future generations will share our preferences and values, remains a worthy problem for both theoretical and applied investigation.

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Part IV
Risk Management: Interdisciplinary Perspectives

Chapter 12
War Rhetoric and Disaster Transparency

Lisa Grow Sun and RonNell Andersen Jones

Abstract In recent years, war and national security rhetoric has come to permeate the legal and policy conversations on a wide variety of natural and technological disasters. This melding of disaster and war to justify exceptions to ordinary constitutional and democratic norms is particularly apparent in governmental restrictions on the flow of its communications in disasters, as limitations on information flow that might be warranted when there are thinking enemies (such as in times of war) are invoked in disaster scenarios lacking such thinking enemies. The extension of wartime transparency exceptionalism into nonthinking-enemy disasters—reflected in both legislation and official rhetoric—is deeply troubling: it risks the illegitimate construction of enemies by government and the unwarranted transformation of public spaces into war zones from which the public can be more easily excluded. Only by consciously disaggregating dissimilar forms of emergencies and removing the rhetoric of war from disaster decision-making can the government make appropriate determinations about the provision of information in times of community or national crisis.

12.1 Introduction

In the years since the September 11 attacks on the United States, scholars and commentators have criticized the emergence of both legal developments and policy rhetoric that blur the lines between war and terrorism (Ackerman 2004). The argument—around which much of the most important constitutional dialogue of the last decade has revolved—is that this blurring inappropriately gives the government, particularly the executive branch, too much power to create and implement measures that infringe upon civil liberties in the name of national security

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A longer version of this chapter first appeared in the UCLA Law Review. See Lisa Grow Sun and RonNell Andersen Jones, *Disaggregating Disasters*, 60 U.C.L.A. L. Rev. 884 (2013). Greater detail on the statutory schemes and governmental actions discussed in this chapter can be found in that article.

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(Kitrosser 2010). Scholars have rightly noted that nebulous labels like the “war on terror” often create unsound justifications for extralegal or extraconstitutional behaviors that threaten to deteriorate core democratic values when stretched beyond their war-specific boundaries (Tushnet 2005).

Unrecognized, but equally as damaging to democratic ideals—and potentially more devastating in practical effect—is the expansion of this trend beyond the context of terrorism to the wider field of nonwar emergencies. Although the constitutional and policy discussions have failed to acknowledge this expansion, war and national security rhetoric has in recent years come to permeate the legal, policy, and scholarly conversations on a wide variety of nonwar emergencies and disasters. Melding disaster and war to justify exceptions to ordinary constitutional and democratic norms is particularly troubling when government restricts the flow of communications in disasters. Although limiting information flow might be warranted when there are thinking enemies (such as in times of war), it is inappropriate in disaster scenarios lacking such enemies. Exceptions to the government obligation of openness and transparency that emerged in the context of a true, calculating adversary may now be invoked in cases of hurricanes, oil spills, wildfires, and pandemics.

The consequences of this melding are grave. Government may wish to invoke national security-like exceptions to justify a lack of information access, lack of disclosure, or lack of honesty in emergencies that are not a war with a thinking enemy. If, however, it is permitted to invoke such exceptions in disasters with a population victimized instead by natural hazards, human error, or technological failing, government abandons its democratic obligations of openness without any of the legitimate justifications warranting deviation from those duties. More significantly, it robs individuals of potentially crucial information at a time when information may be most necessary and valuable.

This chapter argues that a close investigation of recent trends reveals numerous ways in which the temptation to meld disaster and war may manifest itself in government information-flow policies, practices, and norms. It suggests that each of these constitutes a failure to distinguish “thinking-enemy” and “nonthinking-enemy” emergencies and can lead to overzealous squelching of governmental communications. Only by consciously disaggregating dissimilar forms of emergencies and removing the rhetoric of war from disaster decisionmaking can the government make appropriate determinations about the provision of information in times of crisis.

Section 12.2 asserts the normative background position that accessibility, honesty, and disclosure are basic obligations of government. It then identifies important reasons for maintaining the background norm of transparency at times of disaster. Section 12.3 describes the exception to transparency norms that arises in wartime, designed to keep sensitive information out of the hands of a thinking enemy who would exploit that information to inflict harm. Additionally, it explores the objections that thoughtful constitutional scholars have raised to the expansion of this “war exceptionalism” to justify access and disclosure limitations in situations that are not true war but instead acts of terrorism. Section 12.4 argues that the expansion of the inappropriate war analogy is broader than has been recognized. It offers evidence that the language and policy of wartime exceptionalism have crept into the fuller realm of disaster scenarios in deeply problematic ways. Section 12.5 critiques this development, setting forth reasons why a war dynamic featuring a thinking enemy that can exploit information should be considered categorically different from nonthinking-enemy disasters created by natural hazards, technological failure, or human error. It argues that the legal and rhetorical melding of dissimilar disasters risks the illegitimate construction of enemies by government and the unwarranted transformation of public spaces into war zones. Finally, this Chapter proposes eliminating legal and policy determinations that erroneously appeal to a war analogy for a disaster scenario.

12.2 The Norm of Transparency

12.2.1 The Virtues of Transparency

Four decades ago, Thomas Emerson published his groundbreaking article *Legal Foundations of the Right to Know* (Emerson 1976), launching a sweeping modern dialogue (Fuchs 2006) about the ways in which a system of free expression might necessarily encompass more than a "negative right to be free of government interferences" (Emerson 1976) and additionally embrace a concomitant "right in the public to obtain information from government sources necessary or proper for the citizen to perform his function as ultimate sovereign" (Emerson 1976).

Although the contours and scope of necessary transparency remain abiding fodder for the legal academy, it is widely assumed that governmental transparency "is clearly among the pantheon of great political virtues," (Fenster 2006) and scholars have articulated supporting justifications for this norm that range from the highly theoretical to the acutely practical.

From a theoretical standpoint, transparency reinforces governmental legitimacy, informs the consent of the governed, and sustains the rule of law. A free flow of information from government to the people in a democracy is a crucial precursor to the exercise of other core rights (Peled and Rabin 2011), and "[w]ithout meaningful information on government plans, performance, and officers, the ability to vote, speak, and organize around political causes becomes rather empty" (Samaha 2006).

From a practical standpoint, transparency helps to uncover and prevent corruption. Louis Brandeis's oft-repeated observation that "[s]unlight is said to be the best of disinfectants" highlights this critical function (Brandeis 1914). Indeed, a background norm of transparency imposes significant costs on those who would threaten the rule of law, elevate "the power of government over the individual," (Pozen 2010) or otherwise violate the public trust, and, equally importantly, puts the electorate in the position of dominance, as it is given the tools to monitor, police, punish, and deter such abuses (Fenster 2006). Transparency thus permits real and meaningful oversight, cultivates confidence in public policy, and incentivizes public-serving actions by those in positions of authority.

In the face of these philosophical and practical claims, the United States has, in the last half century, taken legal steps to embrace the norm of transparency both constitutionally and statutorily.

12.2.2 Transparency in Disasters

Transparency's virtues persist in times of disaster, both because the general theoretical and practical justifications for a background norm of transparency are not altered by the existence of a disaster and because additional theoretical and practical reasons unique to the disaster context may heighten the need for transparency.

As a starting matter, the theoretical rationales for governmental transparency outlined above resonate within the disaster context. During disasters, the people rely on government representatives to offer a reliable, accurate, and undistorted flow of information. Nearly every theoretical foundation for governmental transparency presupposes a citizenry actively engaged in information seeking. One of the primary critiques of these theories has been that the participants in a democracy are actually more complacent, less engaged in communications with government, and less interested in gathering the information that government might provide (Fenster 2006). However, strong evidence suggests that citizens threatened with immediate disaster do, in fact, actively consider multiple sources of information about risks and appropriate responses (Lasker 2004). They behave as active decision-makers and more closely parallel the idealized citizen envisioned by democratic theorists than do citizens in virtually any other context (The Working Group on "Governance Dilemmas" in Bioterrorism Response 2004).

Moreover, the theoretical support for transparency may even extend in the disaster context beyond the core rationales commonly asserted by transparency scholars. An additional, underappreciated rationale is the risk of information paternalism (Stone 2004). The classic "search for truth" (Stone 2004) rationale for the First Amendment prohibits government attempts to stifle individual citizens' contributions to that search for truth. Likewise, government information withholding predicated on the notion that the public will use that information to form misguided beliefs should also be seen as running counter to the basic principle "that it is better for each of us to decide these things for ourselves than for government to decide them for us" (Stone 2004). Government is, of course, entitled to try to influence citizens' beliefs and actions by persuasion, but not by outright information withholding or misrepresenting what is known. While such information withholding does not itself violate the First Amendment, it can be seen as a government attempt to manipulate individual belief formation that strikes at the core of personal autonomy (Gowder 2006). Such government deception and attempts at thought control reflect a basic lack of respect for its citizens, and undermine citizens' self-determination and autonomous viewpoint development.

Times of disaster have the potential to play a particularly important role in belief formation, as crises may force citizens to confront profound moral questions—questions central to individuals' conception of their selves and notions of the so-called "good life"—such as the extent to which they are willing to prioritize small risks to their own safety over much greater risks to others. Rather than circumventing citizens' consideration of deep moral issues by making those questions appear to be easier and less morally weighty than they are, government can, if necessary, forbid citizens from pursuing certain courses of action that it concludes undervalue the interests of others. Thus, while government is free to prohibit citizens from undertaking certain emergency protective measures (like evacuating a particular location or consuming a particular drug) and is free to bring government force to bear to enforce those prohibitions, that coercive power should not usually include the power to manipulate or withhold information in an attempt to convince citizens of the wisdom of the government policy at issue. Such manipulation poses serious risks not only to individual autonomy but also to government accountability for its policy choices. Indeed, "secrecy is the ultimate form of regulation because the people don't even know they are being regulated" (Podesta 2003). Just as there is a strong preference for government restriction of action rather than of speech (Stone 2004), there ought to be a strong preference for government restriction of action rather than of information.

The practical justifications for transparency are likewise heightened in times of disaster. If government is viewed as untrustworthy or inept, then transparency serves as a critical check on those in power and sunlight offers a disinfectant (Brandeis 1914) to the poor choices that officials might make. This is particularly important in the disaster context because of the broad, and often unreviewable, discretion often granted to executive officials to respond to disasters (42 U.S.C. §§ 5170, 5170a 2006). If, on the other hand, one conceives of government as competent, well intended, and effective in disaster response, transparency is likewise crucial to its ongoing operations on behalf of the citizenry. One challenge faced by a well-intentioned government is to signal to its constituents that it is trustworthy and ought to be obeyed (Posner and Vermuele 2010). Information withholding or manipulation in disasters threatens to undermine public trust in government (Osnos 2011; Hommerich 2012), which in turn will likely undermine public compliance with emergency response instructions (Annas 2010; Lasker 2004).

Reports on a variety of different disasters have suggested that withholding disaster-related information from the public, even for arguably good reasons, may undermine public trust in government institutions (Osnos 2011; Hommerich 2012; National Research Council 2012), and that public anger and distrust is particularly likely when the information withheld from the public would have allowed individuals to make better, more informed decisions about their own safety (Osnos 2011). Any government that wants to ensure voluntary compliance with its disaster recommendations should recognize that dishonesty or withholding of information undercuts both public trust and public compliance (Bratspies 2009).

This is not to say, of course, that full transparency without exception would be either desirable or workable in the disaster context. As in all contexts, competing values and concerns must be weighed in crafting individual laws and policies. Government may also face disaster-specific barriers to information flow, including legitimate concerns about how much information can be effectively communicated and absorbed, limitations brought about by compromised communications infrastructure, and concerns about diverting resources away from problem solving and response and toward information gathering and communication. Nonetheless, this Chapter seeks to demonstrate that the strong background norm of transparency translates into the disaster context and that the importation of wartime exceptionalism threatens to subvert that norm in several ways. The melding of war and disaster skews the balancing toward secrecy and obscures the array of other interests that should be more carefully considered in formulating disaster information policy.

12.3 War Exceptionalism

12.3.1 The Thinking Enemy

Notwithstanding the strong background norm of governmental information flow and the solid status of transparency as a democratic prerequisite, one clear exception to these principles has been almost uniformly embraced—war exceptionalism.

Both the enforcement of positive limitations on private speech and the cessation of the government obligations of information flow and transparency have been recognized as necessary and appropriate when designed to thwart the purposeful exploitation of the information by a thinking enemy (Snepp v. United States 1980). Although the scope of these exceptions has been hotly debated, and concerns over their inappropriate invocation run deep (Posner 2006), even the most ardent proponents of government accessibility and transparency acknowledge at least the “very narrow” brand of war exceptionalism that calls for protecting “sensitive national security data” from enemy exploitation (Emerson 1976).

War exceptionalism has been incorporated doctrinally into common law, legislative, and constitutional schemes that otherwise carry a strong presumption of access and transparency. At the Virginia ratifying convention in 1788, for example, George Mason said, “[i]n matters relative to military operations, and foreign negotiations, secrecy [is] necessary sometimes” (Halperin v. CIA 1980). Likewise, the Freedom of Information Act has an explicit national defense exception (5 U.S. C. 552(b)(1)(A)–(B) 2006), informed by pre-existing executive schemes for classification of national security information plainly designed to thwart thinking-enemy exploitation. Furthermore, the U.S. Supreme Court has recognized that war exceptionalism may justify even prior restraints on free speech as to military information that could be exploited by those who would harm national security (Near v. Minnesota 1931).

12.3.2 War Exceptionalism in Terror

Although war exceptionalism in its narrowest form is largely uncontroversial, in the years since the September 11, 2001 attacks, it has become a topic of vehement debate, as scholars, civil libertarians, and media organizations have criticized the government for what has been described as an unjustifiable, pretextual, and undemocratic expansion of the exception to the "war on terror" (Zolla 2003; Carter and Barringer 2001). While this uproar has been occurring, government decision-makers have likewise engaged in an unacknowledged expansion of this exceptionalism to the realm of natural and technological disasters. This expansion is all the more incongruous and troubling because of the fundamental differences between natural disaster and war. War and terrorism at least share the core commonality of a thinking enemy, but most disasters do not.

12.4 The Melding of War and Disaster

The bleed of wartime secrecy justifications beyond the terrorism context and into the even less analogous disaster context has come about through several subtle but significant means. Legislatively, classic wartime exceptionalism has been extended in state sunshine laws not only to terrorism, but also to nonthinking-enemy disasters. Beyond this, the rhetoric of war has also been making steady inroads into both official and public discourse about natural and technological disasters.

12.4.1 State Sunshine Law Exemptions

The events of September 11 spurred a wave of legislative activity creating new exceptions to state open meetings and records laws. This expansion of longstanding wartime exceptionalism to cover the country's new enemies—terrorists—also swept within its ambit a range of natural disasters, as many of these new state sunshine law exceptions apply by their terms to both terrorism and other categories of disasters.

Nearly 20 states, for example, passed new open meetings exceptions with language that appears to allow invocation of the exception in both terrorism and nonthinking-enemy disaster situations. A similar number of states also passed exceptions to their state open records laws for records related to public safety threats, whether those threats are posed by terrorism or some other type of disaster. In combination, these statutes could prove quite expansive in practice.

The conflation of war, terrorism, and other disasters for purposes of public information policy—a phenomenon accelerated and solidified by September 11—obscures the important distinction between thinking- and nonthinking-enemy situations. Moreover, equating terrorism and nonthinking-enemy disasters in state sunshine laws provides both political and legal cover for state decision-makers who are inclined to conceal disaster information from the public.

12.4.2 Disaster as War: War Rhetoric and the Public Narrative of Disaster

The temptation to meld disaster and war has manifested itself, not only in the expansion of state sunshine laws, but also in the framing of the public narrative of those disasters. Indeed, war rhetoric today plays an increasingly prominent role in the narrative of both natural and technological disaster response (Annas 2010; Gerwin 2011; Ingalsbee 2006; Tierney and Bevc 2007).

The connection between natural disaster and war is not new. Federal disaster management in the United States had its roots in civil defense, and early federal disaster programs were the purview of defense-related organizations such as the Office of Civil Defense of the Department of Defense (Tierney and Bevc 2007). Moreover, the earliest disaster sociological research was funded by the federal government during the Cold War—when the threat of nuclear attack weighed heavily on the American psyche—in the hope that understanding public response to natural disasters could yield important insights for understanding potential civilian response to nuclear attack (Tierney et al. 2006; Sun 2011). Over time, however, this initial impetus seems to have been turned on its head: Rather than looking to natural disasters to understand and frame how citizens might react to a war emergency, both the press and policymakers have begun drawing on war rhetoric to understand and frame natural disasters (Tierney and Bevc 2007; Sun 2011).

When Hurricane Katrina struck on August 29, 2005, just four short years after the September 11 attacks, war rhetoric quickly emerged as a powerful driver of both public perception of the disaster and official decision-making (Tierney and Bevc 2007). The war described by officials and the media was not a war against nature, as one might expect, but a war waged by Katrina’s victims against their would-be rescuers and fellow survivors (Tierney and Bevc 2007; Sun 2011). Early in the coverage of Katrina, reports began “characteriz[ing] the events in New Orleans as the equivalent of war—and, more specifically, the urban insurgency the U.S. military [] face[d] in Iraq [at the time]” (Tierney and Bevc 2007). The lead news story in the Los Angeles Times, for example, reported National Guard troops taking “positions on rooftops, scanning for snipers and armed mobs as seething crowds of refugees milled below, desperate to flee" while "[g]unfire crackled in the distance" (Barry et al. 2005).

War rhetoric not only infused media reporting about Katrina but also shaped public officials' characterization of the disaster and their view that a military response was appropriate. For example, shortly after Katrina made landfall, FEMA Director Michael Brown advised President George W. Bush to invoke the Insurrection Act, which would allow the president to federalize the National Guard and invest law enforcement authority in both federalized national guard troops and active-duty federal military, because reports of "shootings and looting" suggested that the security situation in New Orleans was "spiraling out of control" and Brown wanted "active-duty troops that are ready, willing and able to kill in that area" (Senate Report Number 109-322 2006).

War rhetoric has also been gaining momentum in the planning for public health emergencies such as pandemics. September 11 and the anthrax attacks later that same year accelerated the evolution of a "new paradigm" identifying infectious disease outbreaks not merely as public health challenges, but as critical national security threats (Cecchine and Moore 2006). Indeed, the post—September 11 national security model of pandemic response imagines the need for aggressive, highly coercive measures such as mandatory quarantine and vaccination enforced against citizens not only by local police, who are likely to be quickly overwhelmed by the task, but by the military (Annas 2010). Thus, in October 2005, President Bush called on Congress to give the executive authority to use the U.S. military to enforce quarantines in American communities experiencing bird flu outbreaks (Bush Pushes for Military to Quarantine Avian Flu Breakout 2005).

Moreover, war rhetoric has also spread to technological disasters and accidents like the BP oil spill. President Obama declared the spill "an assault on our shores," and pledged to "fight back with everything that we've got" (Obama 2010c). The President also repeatedly invoked battle imagery to describe the spill response (Obama 2010a), and described his proposed response as "our battle plan … going forward" (Obama 2010b). Other federal, local, and state officials also described the spill response as a war effort.

12.5 War, Disasters, and Security

The legal and rhetorical melding of war and disaster described in Sect. 12.4 presents real, concrete risks to government openness and press access during disasters, and thus to effective and appropriate disaster planning and response. War rhetoric frames public discourse about appropriate disaster management and justifies measures like information withholding that would otherwise clearly appear troubling. The statutory extension of wartime transparency exceptionalism to cover nonthinking-enemy disasters, in turn, provides legal cover for the lack of transparency that the war framing both suggests and legitimizes.

Of course, not all war melding and war rhetoric are created equal in terms of the harm they may generate. Conceptualizing disaster as war is in some respects less problematic than conceptualizing counterterrorism as war. Unlike the war on terror, most disasters will come to an end, as will their immediate consequences, so—absent a prolonged sequence of truly catastrophic events—the disaster-as-war is unlikely to devolve into a never-ending conflict against a vague and shifting threat. Moreover, disaster wars are considerably less likely than the war on terror to lead to traditional wars.

Nevertheless, the disaster-as-war paradigm (Tierney and Bevc 2007) has important real-world consequences that should not be ignored. For one, society may fail to recognize that the war metaphor is, indeed, just a metaphor—an incomplete representation of reality, and one with "powerful consequences" (Sontag 2002). The heavy involvement of the military in much disaster response and the historic pedigree of disasters as potential "states of exception," (Lauta 2012) outside the normal legal structure, create a serious risk that policymakers, and even the public, will forget—at least for truly catastrophic disasters—that war is merely metaphorical.

Moreover, for purposes of information policy, in particular, the melding of war and disaster is even more troubling than the melding of war and terrorism, because while the thinking-enemy rationale for war transparency exceptionalism has at least some currency in the context of terror, it has no application to natural disasters or technological accidents. Beyond the "reflexive secrecy" that war rhetoric may spawn (Mongoven 2006), the bleed of war rhetoric into disasters may encourage the construction of enemies from whom information can justifiably be withheld and the transformation of public spaces into war zones from which interested citizens and press can be more easily excluded.

12.5.1 War Enemies

The prevalence of war rhetoric in disasters may exacerbate many of these already-existing temptations toward secrecy by building on preexisting fears about public reaction to disasters to identify the public (or segments of the public) as "enemies" from whom information can justifiably be withheld. Every war requires an enemy, and disasters-as-war are no exception. Indeed, Schmittian notions of the state of exception are undergirded by the friend/foe distinction (Schmitt 1932). Thus, the expansion of war rhetoric into nonwar disasters spurs and perpetuates the hunt for enemies and justifies what we term "enemy construction" when clear enemies are otherwise lacking. Those constructed enemies may then stand in for the thinking enemy of war and terrorism, suggesting that disasters are thinking-enemy situations like war and terrorism that may warrant withholding disaster information from the public (or even distorting that information) to prevent its exploitation by the enemy.

Section 12.5.1.1 identifies likely candidates for enemy construction during disasters: (1) the "panicking public" at large; (2) the "worried well" who consume resources needed by those who are more at risk; (3) the "overly complacent" who are disinclined to comply with government orders to, for example, evacuate; (4) the "dissenters" or "impeders" who disagree or interfere with the government's chosen response; and (5) the allegedly "lawless" who break the law and may even incite violence.

Finally, Sect. 12.5.1.2 will suggest a wide array of reasons that such enemy construction is troubling. First, these potential enemies lack the characteristics of the thinking enemies of war and terror and should not be equated with thinking enemies for purposes of information policy. Second, much of this enemy construction builds on fears about typical human reaction to disaster that are largely unfounded and grounded in myth rather than empirical evidence. Third, even to the extent that the governmental fears are warranted, withholding information is likely to be counterproductive, subverting the very goals the government purportedly seeks to achieve. Fourth, enemy construction risks becoming a vicious cycle in which the existence of enemies justifies government information control and the government then uses that measure of information control to further vilify and construct enemies. Finally, the segments of the population most likely to be singled out as "enemies" are poor, minority communities and individuals.

12.5.1.1 Potential Candidates for Enemy Construction

The "Panicking Public"

An obvious candidate for enemy construction during disasters is what might be called the "panicking public." One of the most commonly articulated government motivations for secrecy and delay of information dissemination during disasters is fear that full, immediate information will cause the public to panic—to react in overzealous, frenzied, unruly, or harmful ways (Ackerman 2006; Posner and Vermuele 2005; Clark and Chesse 2008; Quarantelli 2001).

Examples of governments withholding information or otherwise downplaying disaster risks to avoid public panic abound in both natural and technological disasters (Fischer 2008). Disaster sociologists have repeatedly observed, for example, that officials sometimes delay calls for evacuation because they fear that an evacuation order will cause people to panic (Fischer 2008; Scanlon 2007; Sorensen and Mileti 1987). In a similar vein, in the aftermath of the March 2011 earthquake and tsunami in Japan, the Japanese government initially withheld from the public government-generated predictions about the likely path of the fallout plume because of fear of "triggering a panic" (Osnos 2011; Onishi and Fackler 2011).

The "Worried Well"

Another potential disaster-as-war enemy is the overreacting citizen who hoards or consumes disaster response resources, at the expense of those who are more directly and immediately at risk during the disaster. Indeed, one of the stronger rationales for allowing government to withhold or manipulate risk information is the fear that people who are at lower risk will consume response resources (such as medicine or evacuation corridors) needed by those who are most at risk. In the public health context, for example, emergency planners often refer to the "worried well" (Center for Disease Control and Prevention, Crisis and Emergency Risk Communication 2002), who might hoard supplies of the antiviral drug Tamiflu® during an influenza pandemic.

Faced with such a possibility, a government official might decide to distort risk information to ensure that limited response resources reach those most in need. She might, for example, choose to underplay the risk to people in certain geographic areas or with certain health characteristics or to overplay the risks associated with treatment in order to discourage those at lower risk from hoarding treatment resources.

The "Overly Complacent"

Another potential candidate for enemy construction in disasters framed as war is a group that might be called the "overly complacent"—those who are reticent to comply with government recommendations because they are not convinced the risks warrant protective action. The most likely information-flow tool government will employ against the overly complacent is overplaying the relevant risks to encourage compliance. For example, a local official who believes that an evacuation is necessary might exaggerate the probability or likely magnitude of a hurricane to spur recalcitrant citizens to comply with her evacuation order.

Alternatively, the government might be inclined to deny the public information in the form of evacuation orders during a current disaster because it fears that, if an order turns out to be unnecessary, people will not comply with a future evacuation order. This "warning fatigue" could potentially be a serious problem, especially for dense urban areas where the long evacuation times required to evacuate large populations mean that evacuations must be called relatively far in advance.

The "Dissenters" or "Impeders"

During wartime, those who criticize or oppose government actions are often cast as disloyal enemies of the state (Stone 2004). The same tendency to expect people to "rally 'round the flag" during disaster wars may result in constructing enemies out of those who publicly question or disparage the government's chosen response measures, or even those who simply seek to subject that response to public scrutiny by exposing what is actually occurring. In the aftermath of the BP oil spill, for instance, the federal government implied that at least some of those who wanted access to affected beaches sought access, not just to document the extent and effects of the spill and the use of dispersants (to which many objected), but to impede the response and damage the boom being constructed to contain and trap oil. This enemy construction, in turn, helped justify access restrictions and other controversial response measures.

The “Lawless”

As the events during Katrina demonstrate, government may attempt to portray some disaster victims as lawless enemies of public order and the public good. Indeed, public officials played a critical role in vilifying Katrina survivors. For example, Louisiana Governor Blanco suggested that troops on the ground in New Orleans were ready and able to shoot to kill survivors who posed a threat (Troops Told “Shoot to Kill” in New Orleans 2005).

12.5.1.2 Critiques of Enemy Construction

Constructed Disaster Enemies Are Categorically Different from Wartime Thinking Enemies

The thinking nature of the war enemy—and that enemy’s ongoing tactical desire to exploit public information to do the country further harm—is critical to the legitimacy of the war exception to government transparency. Constructed disaster enemies will almost always lack these fundamental characteristics and are thus categorically different from wartime enemies. Accordingly, the construction and invocation of these “enemies” should not be sufficient to justify importing wartime transparency exceptionalism into these other disaster contexts.

The “panicking public” enemy is easiest to distinguish from the thinking enemy of terrorism. Indeed, the rationale for withholding information to stave off panic identifies the public not as a thinking enemy who will exploit government disaster information to do further harm but instead as a foolish and irrational (even unthinking) enemy whose poor response to disaster information unintentionally exacerbates their own risk. The primary justification, then, for information control to tamp down panic rests on a paternalistic notion that, if people are going to act in ways that increase their exposure to harm during disasters, government should protect the public from its own flawed impulses by manipulating the public understanding of the situation.

In the face of the substantial uncertainty that many disasters create, there often will be little reason to think that official decision-making is superior to individual weighing of the risks. However, even if official decision-making is more likely to get it “right” than individual decision-making, there is something particularly offensive about information paternalism that distorts or withholds information in order to manipulate people’s disaster response choices.

While government-imposed restrictions on taking certain protective actions would also infringe on people’s autonomy, at least citizens would then be in a position to understand and protest those restrictions and hold officials accountable. Information restrictions or distortions, in contrast, interfere in a more fundamental way with people's decision-making and ability to hold their leaders accountable.

The "worried well" arguably have more in common with the thinking enemy of war and terrorism than the panicking public at large because their actions may selfishly compromise the safety of others as they hoard or consume resources needed by those most at risk. Because of this potential risk to others, the worried well deserve separate consideration as potential enemies whose existence might justify information suppression, as the rationales for doing so extend beyond paternalism.

At least two factors, however, distinguish the worried well from the prototypical thinking enemy of war or terrorism. First, they differ radically from the thinking enemy in how they use information. Unlike a terrorist who exploits government information about public vulnerabilities to plan a second attack, the worried well would not be exploiting the government information to do further planned harm with that specific information. In most situations, the worried well do not actually wield government-provided information as a weapon in and of itself. Rather, the government would be withholding or distorting information, not to prevent its exploitation, but to keep people in the dark about their own circumstances and risk in hopes that they would be dissuaded from overreacting and unnecessarily consuming limited resources. The analytical difference between a terrorist who uses information about a structural vulnerability in a power grid to plan a deliberate attack on that structure and a citizen using that same information to decide to hoard generators is a difference in kind, not merely of degree. It is a difference that makes the war analogy, and the information-flow exceptionalism that accompanies it, inapt.

Second, the worried well lack any kind of specific intent to do other disaster victims harm (even if they are aware that their actions may make it more difficult for others to avoid harm). When they consume response resources, they usually do so out of a genuine belief that those actions are necessary to keep themselves and their families safe.

Intentionality matters both as a moral matter and because government usually has more tools at its disposal—beyond information control—to prevent harm caused unintentionally than harm caused intentionally. While the government is unlikely to be successful in persuading terrorists to abandon their goals, in the case of the worried well, government can educate the public about the risks that might be confronted, take other planning measures to reassure the public, or even forbid certain problematic behavior. When these other information-friendly avenues exist, government should not be allowed to resort to information control to achieve its ends.

This same basic analysis applies to both the "overly complacent" and "dissenters" who, to the extent they do harm to others (by, for example, endangering first responders who attempt to rescue those who failed to comply with evacuation orders), do so unintentionally and do not wield public information as a weapon to harm others.

Thus, the "lawless" who resort to looting and violence after disasters are the only constructed enemy who may truly resemble the thinking enemy of war and terrorism (5 U.S.C. § 552(b)(7)(A), (E)–(F)). However, as the next Subpart will demonstrate, the assumption that lawlessness will be a major problem after most disasters is without empirical support.

Enemy Construction Rests on Faulty Empirical Assumptions

In addition to suggesting falsely that enemies akin to thinking enemies lurk in the shadows of every disaster, disaster enemy construction typically rests on a number of faulty empirical assumptions, including the assumptions that those experiencing disaster will panic and engage in antisocial, criminal behavior.

No one disputes that many disaster survivors will experience fear. Nevertheless, leading disaster sociologists long ago concluded that the belief that panic is a common reaction to disasters is a "disaster myth"—a widely held misconception about postdisaster human behavior (Quarantelli and Dynes 1972; Sun 2011). Indeed, even though disaster panic is apparently presupposed by even preeminent transparency scholars (Pozen 2010), sociologists contend that the finding that postdisaster "panic is rare" is one of "the most robust conclusions" to emerge from more than 50 years of disaster sociological research (Clark and Chess 2008).

Empirical evidence suggests that survivors of many kinds of disasters create a kind of altruistic community in which preexisting social conflicts are suspended for a time to focus on the needs of the community in the immediate aftermath of disaster; indeed, selfless behavior is often observed in disaster's aftermath (Picou et al. 2004).

Furthermore, much of what might be characterized as antisocial behavior or panic in the wake of disasters—such as disobeying government orders to evacuate or shelter in place—is easily explainable on other grounds. People disobey government instructions for reasons other than panic or clear antisocial aims. For example, in a New York Academy of Medicine study of likely public reactions to a dirty bomb attack, the vast majority of those who reported that they would likely defy a "shelter-in-place" recommendation did so because they prioritized attempting to ensure the safety of their children and others dependent on their care (Lasker and New York Academy of Medicine 2004). Similarly, people sometimes fail to heed hurricane evacuation warnings because they are unwilling to leave family pets behind. While some hoarding behavior by the worried well might be expected, the amount of truly antisocial activity in the aftermath of disasters (including looting and violence) tends to be greatly exaggerated.

Information Withholding Is Counterproductive

Even if government were entirely correct in its assumptions that the public was likely either to panic and overreact or to be overly complacent in the face of disaster, the denial, omission, or manipulation of information is precisely the wrong way either to avoid public panic or to ensure compliance with official recommendations. Indeed, such information withholding is likely to backfire and subvert the government's alleged goals.

Some sociologists have suggested, for example, that by withholding information, government may, in fact, spur panic where little would otherwise have existed (Barry 2004). Moreover, as Sect. 12.2 detailed, withholding disaster information from the public tends to undermine public trust, which in turn undermines public compliance with government disaster recommendations. Social science also suggests that the best remedy for potential problems such as "warning fatigue" is more public information, rather than less.

Enemy Construction Risks a Vicious Cycle

As the events during Katrina demonstrate, the relationship between government control of information and enemy construction can run in two directions. First, as described above, government can use enemy construction to justify information withholding. Second, as Katrina illustrates, the government can attempt to use whatever control over information it has to shape the public narrative of disaster in order to construct enemies. Official overplaying of the risks of postdisaster violence—itself a form of information distortion—was key to the demonization of Katrina survivors and their construction as a wartime enemy. Moreover, while the media were, without doubt, key propagators of the wartime imagery of Katrina, restrictions on journalists attempting to document clashes between security forces and alleged looters may nonetheless have helped government officials perpetuate this narrative of Katrina survivors as aggressive enemies of public order, rather than victims.

This phenomenon suggests the possibility of a vicious cycle in which information control aids enemy construction, and the constructed enemies can then be invoked to justify further information control and withholding. Thus, governmental attempts to manipulate information to create new enemies warrant both heightened skepticism and heightened concern.

Enemy Construction Targets the Poor and Minorities

Finally, as the experience of Hurricane Katrina suggests, the segments of the population most likely to be singled out as "enemies" during a disaster are poor minority communities and individuals. The identification of enemies is likely to follow predictable paths, influenced by both racial and class prejudice. Indeed, enemy construction is likely to be the most persuasive when the enemy is a clearly delineated, "well-defined" "other"—an other that unambiguously excludes most of the affected population (Gross 2003).

Additionally, vulnerable groups are particularly likely to be constructed as enemies because they are often the most distrustful of government and thus the most likely to question and resist compliance with government recommendations (Lasker and New York Academy of Medicine 2004). This result is particularly troubling given that the impacts of disaster are already typically concentrated on poor and minority populations (Farber et al. 2010), who may then also be both demonized and deprived of information about the very substantial risks they face.

12.5.2 War Zones

In addition to encouraging enemy construction, war rhetoric encourages and justifies public officials' transformation of disaster-affected public spaces into war zones where information is controlled and from which the public and press are partially or wholly excluded. While there is little doubt that areas ravaged by disaster can resemble a war zone and that some access restrictions are justified by genuine safety concerns, labeling domestic disaster sites as "war zones" tends to suggest that officials have both unfettered power and compelling justification to close such areas to public scrutiny. This war mentality may embolden public officials in adopting overbroad limitations on access to the area, and the war framing may help disguise other, less public-serving motivations for such access limitations. Limited public and press access to disaster sites, in turn, limits public information about the incident, response measures taken to manage the disaster, and the ongoing risks to public safety.

This "war zone" transformation has been observed in the aftermath of Katrina, during wildfires, and in the response to the BP oil spill. The repeated identification of post-Katrina New Orleans as a "war zone," (Tyson 2005; Yassin 2005; Troops Told "Shoot to Kill" in New Orleans 2005) and the heavy military and police presence that rhetoric justified, likely contributed to restrictions on journalists' ability to observe and document the official response, as well as the terrible human toll of the disaster. At least some journalists in post-Katrina New Orleans encountered official resistance from both military and law enforcement personnel to their attempts to cover the Katrina disaster and the bungled governmental response. NBC News anchor Brian Williams, for example, reported that a sergeant prevented him from photographing a National Guard unit "taking up positions outside a Brooks Brothers on the edge of the [French] Quarter" (Williams 2005).

Even after the New Orleans Convention Center and Superdome were secured, journalists reported that the National Guard refused journalists access to those shelters (Kurtz 2005). Moreover, FEMA attempted to dissuade journalists from photographing the bodies of Katrina victims, thereby discouraging journalists from capturing and conveying the full impact of the storm (Kurtz 2005). This apparent attempt to downplay the true human cost of the disaster on those left behind in New Orleans, while overplaying the violence of Katrina survivors and constructing post-Katrina New Orleanians as lawless enemies of public order, is in some respects the most pernicious combination imaginable, as it both minimizes the suffering of victims (thus minimizing government responsibility) and implicitly blames the victims themselves for whatever suffering did occur.

Wildfires provide other examples of the transformation of public areas affected by disaster into disaster war zones. The wildfire war zones, from which members of the press are often excluded and residents may be forcibly evacuated, can extend well beyond those areas directly affected by the fire (Ingalsbee 2006). For example, during the 2002 Biscuit Fire in southern Oregon, "[t]he entire Siskiyou National Forest—over 17,000 square miles—was closed to the public" (Ingalsbee 2006). As one former firefighter and longtime observer of federal firefighting policy observed:

> Armed federal agents, at times even supplemented with actual military personnel, enforce the [sweeping] closures to ensure that members of the public or the press do not infiltrate into fire camps or combat zones. Much as occurred on the Grenada invasion and the Gulf War, reporters are herded around fires in official press pools. . . . In this militarized situation of highly restricted access and tightly controlled information, the public is utterly dependent on the government's version of events (Ingalsbee 2013).

Restrictions on media access to several wildfires raging in the western United States during the summer of 2012 also illustrated these concerns.

The response to the BP oil spill was likewise marked by the transformation of public beachfront and waters into war zones where public access was sharply curtailed. The New York Times reported that "[j]ournalists struggling to document the impact of the oil rig explosion have repeatedly found themselves turned away from public areas affected by the spill, and not only by BP and its contractors, but by local law enforcement, the Coast Guard and government officials" (Peters 2010). Indeed, while many access restrictions may have originated with BP, ample evidence suggests that local officials were often complicit with BP in enforcing these restrictions (Peters 2010).

The Coast Guard itself established a 65-foot "safety zone," making it a federal felony to come within 65 ft of a boom or "oil spill response operations" without explicit authorization from the Coast Guard (U.S. Government 2010; National Press Photographers Association 2010). An Associated Press reporter noted the parallels to embedded reporters covering military campaigns in Afghanistan, explaining that "[t]here is a continued effort to keep control over the access . . . [a]nd even in places where the government is cooperating with us to provide access, it's still a problem because it's still access obtained through the government" (Peters 2010). It is difficult to escape the conclusion that the notion that the country was at war—at times with the oil, at times with BP, and at times with intermeddlers like the press who might impede the official response operations—emboldened government officials to limit the public's ability to witness and document both the scope of the harm and any flaws in the government response. Indeed, Admiral Thad Allen explicitly used the rhetoric of war to justify the overreaching access restrictions (Safina 2011).

12.6 Conclusion

The expansion of wartime transparency exceptionalism is more extensive than has been appreciated, and its invocation in nonthinking-enemy disasters carries with it ramifications that are, as a practical and theoretical matter, as serious, if not more serious, than those that have been the exclusive focus of our constitutional dialogue on war exceptionalism for the last decade. The melding of war and disaster, reflected in both legislation and official rhetoric, leads the government to construct enemies from whom it can justifiably withhold information and to transform public spaces into war zones from which citizens and press can be more easily excluded. The aggregation of war with dissimilar non-thinking enemy disasters is particularly troubling because it subverts the background norm of transparency that should exist during disasters and is likely to distract from or overshadow the more careful and nuanced balancing of other competing values that might warrant narrower exceptions to this norm.

Now is the time to use this new awareness of the conflation of war and disaster to critically assess the tone and language used to convey disaster information and policy, the care with which legislative exceptions to transparency are crafted, the common treatment of disparate types of events in emergency power legislation more generally, and the structure of agencies and entities with responsibilities during these critical times.

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Chapter 13
Participatory Decision-Making on Hazard Warnings

Gordon Woo

Abstract There are many hazard situations where there is significant uncertainty over whether a dangerous event will actually materialize and threaten a populated region. In the presence of such uncertainty, hazard warnings may be issued to motivate a diverse range of mitigating actions that might reduce the risk of casualties should a major natural hazard event occur. Most of these possible actions involve the active cooperation of citizens in the region affected. Guidelines for the involvement of citizens in the decision-making process are identified, with a focus on key principles that provide a platform for participatory decision-making. These principles include the democratic right of citizens to information and choice; the need for basic training and education on risk issues to enable citizens to make more evidence-based decisions; the opportunities for governments to nudge rather than coerce citizens into taking actions; the scope for application of the precautionary principle; and the over-arching need for decisions to be rational, equitable and defensible.

13.1 Introduction

This chapter reviews and assesses the involvement of citizens in the decision-making process on hazard warnings. There are substantial advantages of citizen participation in government decision-making. People can learn by interacting with the government, and influence thinking through sharing their knowledge and views. In turn, the government can also obtain information feedback from the people on societal matters of concern, and can build trust with citizens, and gain legitimacy for risk decisions that are made. Through active involvement, gridlock can be broken, and citizens can have some direct democratic control over the policy process, leading to better policy and implementation decisions (e.g. Renn 2008).

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The acceptability and tolerability of societal risks can be defined in terms of the functionings and capabilities of individuals (Murphy and Gardoni 2006, 2007).

But as with many public policy issues involving environmental risks, guidelines for the involvement of citizens present a major challenge. This is especially true of technical and scientific matters, about which the general public may have little knowledge, and may indeed be misinformed. Public ignorance and lack of understanding are a longstanding obstacle to increased public involvement. Even with regard to a common meteorological peril such as lightning, more than half of Americans cannot explain why lightning is seen before thunder is heard (Kramer 2013). Despite more than three centuries of scientific progress since the European Enlightenment, a high proportion of the population in industrialized nations still have a minimal pre-Galilean knowledge of science, reading more about astrology than astronomy, and holding primitive beliefs about earthquakes that date back before the science of seismology was established. This is exemplified by the credence still given to the notion that earthquake disasters may be divine retribution (Smits 2014).

Quite apart from scientific ignorance, the individual attitudes, beliefs and motivations of people may limit their potential to contribute to complex policy decisions (McCallum and Santos 1997). Indeed, environmental policy centered solidly on public risk perception may fail to protect human health adequately. On the other hand, as shown by disagreements within the scientific community and expressed in the scientific literature, there are fundamental limitations to the extent of expert scientific knowledge, which are reflected in a significant level of risk ambiguity. Public suspicion over risk analysis is not without foundation; there have been regrettable historical precedents for relevant risk data being wilfully concealed or ignored (Rowe and Frewer 2000). So some element of public oversight should be welcome by both scientists and decision makers if future acrimonious confrontation and litigation over decision-making are to be avoided.

But whereas some degree of community participation in government decision making produces notable benefits, lengthy inclusive public inquiries can be both costly and ineffective (Irvin and Stansbury 2004), and also there may be fundamental conflicts of interest. A government has a responsibility for society at large, not least for those whose voices are not heard through lobbying. Furthermore, whereas people tend to discount future risks and be complacent about them, government policy should address and manage future risks, even if these may be well beyond the time horizon of most citizens. The risks from climate change are an obvious and important example.

Complacency also may apply to current rare risks that many if not most citizens may never have personally experienced. Earthquake risk is the foremost example. The comparatively low level of public participation in US voluntary earthquake drill exercises, and purchase of earthquake insurance, are symptomatic of a tendency for citizens to avoid worrying about occasional hazards they may hope, with luck and optimism, never to experience for years or decades. More urgent pressures of daily living govern their concerns, fears and lifestyles. Given such human optimism bias, there is clearly an important role for a degree of top-down administrative decision-making to preserve and maintain overall societal interests. Participatory decision-making is desirable in democratic principle, but there are limits to which it can be successfully implemented.

Every seismic crisis is also an economic crisis for the region impacted, and for the people who reside or work there. Their lives and livelihoods may be affected to a greater or lesser extent. Accordingly, behavioral economics and social psychology are important disciplines that need to contribute to the practical analysis and viability of earthquake hazard warnings. In particular, the involvement of citizens in the decision-making process implicitly requires an appreciation of the way that individual citizens make decisions for themselves and their families in times of crisis.

This appreciation is best learned well in advance of a future seismic crisis, rather than in real time. An integral part of disaster preparedness is decision preparedness: having the advance knowledge to make a rational and informed decision when it is needed. For example, civic authorities should be very familiar with the regional population geography, and provision should be made for families, including children and even pets, to stay together during a crisis. This can present sizeable logistical challenges that are hard to address satisfactorily during the chaos of an actual crisis when communications are restricted and human resources are scarce, but may be tackled ahead of such a time.

13.1.1 Evaluation of Public Participation Methods

The promotion of democratic ideals and principles, trust in government regulators, and transparency in the overall regulatory process are ostensibly desirable outcomes better served by raising the level of public participation. There are different ways of achieving the goal of increasing public participation, which differ in their relative usefulness and value. From the supply and distribution of risk information and questionnaires, to the setting up of special focus groups to gauge public opinion on sensitive and complex safety issues, to the selection of public representatives for committee membership, active engagement with the public on risk issues can take many diverse forms.

Before guidelines can be established for the involvement of citizens in the decision-making process, there needs to be a systematic framework within which alternative public participation methods can be evaluated. Token involvement of the public serves little purpose beyond public relations approval. To meet this objective, evaluation criteria have been broadly identified by Rowe and Frewer (2000).

Two principal considerations for evaluating public participation methods are the way that procedures are effectively constructed and then accepted by the public. If a procedure and its recommendations are accepted by the public, but the ultimate decision is arrived at in an ineffective manner, then its implementation may not be constructive. Even if a procedure is effectively constructed, the procedure may fail if it is perceived to be unfair or undemocratic. Fairness and competence are two attributes that are widely agreed to be desirable elements of any procedure. Other acceptance criteria, as formulated by Rowe and Frewer (2000) are elaborated below.

13.1.1.1 Representativeness

The public participants should comprise a broadly representative sample of the population of the affected public, and not just be a self-selected minority eager to exercise a strong locus of control and actively exert influence over their own future. Caution needs to be taken to avoid disadvantaging poorer and less educated members of the public, as well as others reluctant or lacking the practical means to engage with officials, or who may not be inclined to involve themselves actively in any public safety dialogue.

13.1.1.2 Independence

The participation process should be conducted in an overtly independent and unbiased manner. Facilitators of the process should be clearly seen to be independent. Professional diversity of members of a management committee would be desirable. This might be achieved by including academics, think-tanks, NGO's and others from neutral non-commercial organizations having an established reputation for promoting the public welfare.

13.1.1.3 Early Public Involvement

Public participation should occur as soon as is reasonably practical. This may not be sensible or viable during the phase of scientific assessment of risk, which draws upon the scientific community. However, at the crucial stage when value judgments become salient and practically important, it is vital to consider also the psychological and sociological aspects of risk, and here the public should always be consulted. Organizational factors may lead to delay, but late involvement of the public may deny some possible risk mitigation measures to the public, such as making alternative accommodation arrangements for the disabled. Late involvement may lead to resentment, regret and recrimination. Perhaps most detrimental to public safety would be long-lasting public mistrust of scientists.

13.1.1.4 Influence

Public participation should have some genuine influence on public policy, and not just be a public relations veneer used to legitimate decisions, or give a superficial appearance of consultation without there being a serious intent to act on the recommendations of citizens. The media may have a helpful role in informing the general public, and reminding decision makers, about ways in which public participation has influenced policy in a meaningful, constructive way.

13.1.1.5 Transparency

Public participation should be transparent so that the public can clearly see what is happening, and understand the procedural mechanics of how decisions are being made. Through transparency, any public misgivings and suspicions may be allayed. Transparency could involve releasing into the public domain information on aspects of the procedure such as the minutes of meetings, and details of the way meetings are conducted and how a compromise decision is ultimately reached.

13.1.1.6 Resource Accessibility

Public participants should have access to the resources needed to enable them to carry out their tasks. In particular, effective decision-making requires access to appropriate and relevant information. This may involve some prior access to human resources such as scientists and risk analysts, who should be willing and able to explain with the required patience some fundamental aspects of hazard science and the role of uncertainty.

13.1.1.7 Task Definition

The nature and the scope of a public participation task should be clearly defined. The effectiveness and credibility of a procedure are prone to be eroded by misunderstandings over the task definition. Potentially, this may lead ultimately to the abandonment of the task if the ultimate authority for decision-making appears to be undermined or circumvented. Of course, some flexibility may be desirable if new circumstances arise.

13.1.1.8 Structured Decision Making

The public participation exercise should provide people with an adequate understanding of the structure of the decision-making process. This would enable participants to appreciate better the underlying reasons to support a decision, as well as the extent to which a conclusion may be justified by the available evidence. The provision of documentation would expedite efficiency and raise transparency, both of which are basic acceptability criteria.

13.1.1.9 Cost-Effectiveness

Public participation procedures should be cost-effective. The extent of major costly public hearings should be commensurate with the importance of a pending decision. Before a participation exercise is conducted, the potential financial and personnel costs of alternative methods should be taken into account to ensure any agreed approach is both financially sound and affordable.

13.2 Information and Choice in a Democracy

One of the defining characteristics of a totalitarian state is the very limited involvement of citizens in the decision-making process relating to their safety from external hazards. Decisions are centralized within a government that is not answerable to its citizens through the ballot box. In matters of public safety as in other spheres of life, the government acts in the self-interest of the state, or as if it knows what is best for its citizens.

One of the consequences of a paternalistic attitude of a totalitarian state is that only a minimal amount of information is passed on to citizens, and what information is ultimately disseminated is highly regulated. More information would be needed for citizens to make an informed choice. However, freedom of choice is just one of the basic freedoms and rights denied to citizens of a totalitarian state. The 1986 Chernobyl nuclear disaster in the Ukraine is one of the most notorious examples of the intentional denial of information access and choice by a totalitarian regime.

13.2.1 Making Available the Best Information

Democracies function quite differently from totalitarian states in citizen participation and the open dissemination of information. The Freedom of Information Act is enshrined as a cornerstone of US democracy. This Act provides for public access to federal files, with a requirement that federal agencies have ten working days to respond. There are also ‘Sunshine’ laws that require public notice of government meetings so that where formal action is taken, the public may attend (Argonne National Laboratory 2013).

As noted by Irvin and Stansbury (2004), a central tenet of citizen participation is the belief that citizen involvement in a Jeffersonian democracy will produce more public-preference decision making on the part of administrators, and a better appreciation of the wider community among the public. Public protest against the government, even on a massive scale, is a basic right of citizens in a democracy. When there is suspicion that information is denied to citizens, protest can turn hostile. King and Stivers (1998) have suggested that improved citizen participation could mitigate a growing deterioration of public trust.

Britain is a country with a longstanding democratic tradition, but its development as a participatory democracy in a sense that President Jefferson would have recognized has been gradual. Regarding information, the Victorian Prime Minister, Benjamin Disraeli (1880), wrote that, '*As a general rule*, *the most successful man in life is the man who has the best information*'. Every human action is the consequence of a decision, which is preceded by a decision-making process, for which information can make all the difference between achieving positive and negative outcomes. Access to information also can make an enormous difference to the way that negative outcomes are perceived. Every decision is conditional on the information available. The regret at a negative outcome is aggravated if a less adverse outcome might have been possible with more information.

Only well-informed citizens can be expected to grasp technically and scientifically difficult situations, and perceive holistic solutions. The more participants with a broad level of technical understanding, the better should be the policy decisions and the social outcomes. In the context of hazards, information is especially crucial to enable citizens to make optimal decisions for themselves and their families. In particular, hazard warnings serve a vital safety role. To paraphrase Prime Minister Disraeli, '*The most successful citizens in dealing with an external hazard are those with the best information.*' In respect of health hazards, governments try to educate the public by disseminating medical information and correcting public misconceptions about the dangers of vaccines and the efficacy of treatments.

With regard to external hazards that might pose a potential safety threat to citizens, information is routinely passed on by democratic governments, even when there is substantial uncertainty over the timing, location and severity of the threat. For the weather-related perils of hurricane, extra-tropical storm, tornado, hail, wildfire and flood, ensemble weather forecasts provided the basis for probabilistic hazard assessments. These are converted into color-coded alerts and explicit hazard warnings, including advisories against avoidable exposure to the elements.

Of the geological hazards, volcanic activity is a notable example where scientific information about the precursory activity is generally available, and where scientific commentary is given about observed temporal changes in activity. Accordingly, in some regions susceptible to both volcanic and seismic risk, e.g. the Caribbean, information about temporal changes in seismic activity, (e.g. swarms or an anomalous number of small events), may be routinely given out to the public with an additional warning message, with the intention that the information may increase hazard awareness and influence population behavior.

13.2.2 Making an Individual Choice

Even during the controlling Maoist regime in China, individual citizens have been able to take some safety initiatives of their own during a period of perceived heightened earthquake risk. According to Lomnitz (1994), a family might move out of its vulnerable home into a nearby earthquake hut, which was a temporary shelter made of branches, wooden planks, and other light materials. Apparently, temporary shelters have also been in historical use in Calabria, southern Italy, and parts of Latin America. But today, earthquake huts are associated mainly with post-disaster shelter.

When a foreshock sequence started around Haicheng, China, in 1975, people did not wait for government instructions. They quickly built makeshift earthquake huts in front of their homes. They did not have to rely on government information about earthquake precursors or form a subjective belief about information accuracy, because they had the sensory cue of actually feeling the tremors directly.

From a psychological perspective, people tend to perceive risk as feelings of various kinds (Slovic 2010), and feeling tremors sends powerful warning signals to the brain. There was thus no need for government warning or supervision when these huts were erected spontaneously because of the aftershock activity. Fortunately, the weather was mild for February, so this community self-organization of seismic mitigating action was practical and did not incur a harsh penalty of extreme discomfort or hypothermia. Beyond the building of living huts, patients were moved from hospitals, the old and weak were moved to safety, transportation facilities were concentrated, and medical teams were organized (Bolt 1988).

Compared with evacuation to a distant area of lower expected ground shaking, moving into a local safe earthquake hut is inherently a much lower cost measure. The twenty-first century analogue of the earthquake hut is the motor car, with the advantage of being readily available with no need for pre-assembly, and affording much better weather protection and personal security. The few fortunate to have access to a caravan would have the discomfort factor reduced. For those aware that they are living in seismically vulnerable buildings, sleeping in a car would be a low-cost option: a rational individual choice for those especially risk-averse and having a strong locus of control.

It is not for a government to suggest, let alone recommend, such a specific risk mitigating measure. Conversely, it is not for civil protection authorities to discourage such individual risk mitigation measures, without making allowance for individual preference, and the extenuating home circumstances that some citizens may be experiencing. The scale of risk aversion is open-ended; there may be some individuals who would be inclined to take evasive action even if the chance of being injured by an earthquake was as low as being struck by lightning.

What might be appropriate and welcome would be a broad general advisory message about the dangers of being in a seismically vulnerable building. This messaging, of course, assumes that occupants have an awareness of the vulnerability of their building through knowledge of its approximate age and construction type. Transparency in identifying vulnerable buildings is a future aspiration for earthquake engineering practice: this would require an extensive program of data capture on building exposure.

In considering the involvement of citizens in the decision-making process, it is important to recognize that, faced with identical hazard information, two individuals may make very different choices of action. Whereas *risk as analysis* attempts to introduce logic and reason, *risk as feelings* is a quicker and easier, more instinctive, intuitive and subjective reaction to danger (Slovic 2010). The way that people react to danger can be affected by mood and personality as much as by the actual danger signs themselves. Slovic has pointed out the dilemma for policy makers in differentiating analytical and experiential human reactions. On the one hand, unwarranted and exaggerated public fears should be assuaged by informed and enlightened scientific analysis; but on the other hand, there should be due respect for public sensitivity to qualitative value-laden considerations that may be intangible.

Especially during a social media era of massive expansion of information technology, transparency in information provision is a pre-requisite for public communication. However, Realpolitik may intervene to impose other priorities. In respect of the terrestrial threat from volcanic eruption, the seismic crisis on the Greek island of Santorini in the winter of 2011–2012 introduced a multi-hazard aspect to individual choice. A series of moderate tremors signified a build-up of volcanic magma that might have led to a volcanic eruption that in turn might have triggered a major earthquake. For those who knew about the significant volcanic hazard, including geoscientists and their families, some personal decisions were made not to visit Santorini in the short-term on hazard grounds.

But in this particular instance, political fright over the desperate plight of the Greek economy, heavily dependent on tourism, over-rode the perceived modest volcano risk in the decision by the UK foreign office not to provide explicit volcano hazard information to British travelers to Greece. Whereas there was website information warning of terrorism and political disorder in Athens, and some mention of the susceptibility of Greece to earthquakes, there was no specific reference to the volcano hazard in Santorini. Political focus on vital international economic issues left little scope for UK citizens to participate in the Santorini hazard warning decision, except potentially for the avenue of the social media.

13.3 Willingness of Citizens to Pay to Avoid Danger

In the absence of regular drills and training, the behavior of citizens in hazardous situations may exhibit some of the anomalous erratic features that Kahneman (2011) has so often pointed out in decision-making. The starting point for fresh thinking about practical risk mitigation is a basic cost-benefit analysis. If the likelihood of a dangerous event is comparatively low, then only measures of commensurate low cost would be contemplated by most people as economically reasonable or practically viable. As the likelihood rises, so more elaborate and expensive measures would be considered sensible, including risk mitigation to reduce the loss consequences of a hazard event, and evacuation to avoid the personal physical risk associated with a hazard event.

However, it is currently rare for public officials to quote likelihoods in a way that would be immediately useful for individuals in deciding on a course of action or inaction. Even where likelihoods are openly available to the public, as with the chances of a hurricane making landfall, or a major earthquake striking California over the next 30 years, further public education and training are required to translate this hazard information into a readily comprehensible and actionable decision-making form. This kind of hazard information should influence where people live, and how vulnerable they permit their homes to be.

13.3.1 Individual Risk Perception in Willingness to Pay

The willingness of an individual to pay to avoid danger is an important consideration in the involvement of citizens in the decision-making process. If people are making decisions for themselves, they should have some familiarity with this concept. For rare events, such as earthquakes, citizens need to gain a basic appreciation of their risks from an early age. Paul Slovic (2010) has speculated that, in the future, new methods of education, starting in the early years, will teach citizens how to understand the reality underlying large numbers of casualties, so that society can act effectively in efforts to halt mass destruction.

Catastrophes are low-frequency and high-consequence phenomena. Apart from being able to understand better the potential for large losses, better early education is also needed to understand the significance of low frequencies for decision-making. What is a one in a hundred risk? What is a one in a thousand risk? Elementary hazard lessons in school can pay off out of the classroom in casualty mitigation.

Having previously watched a video of a Hawaiian tsunami in a school geography class, when 10-year old English schoolgirl Tilly Smith saw the water recede and froth on a beach in Phuket, Thailand on 26 December 2004, she had the presence of mind to shout a tsunami warning, so saving the lives of those on the beach. She could not have been sure that a life-threatening tsunami for coming, but the beach-time disruption cost was low compared with the expected life-saving benefit. She later became an international UN school ambassador, sharing her story of the value of hazard education with children in other countries. If schoolgirls could also be taught the elements of chance and risk besides geography, then the assessment of risk might be less dominated by just the gut feeling of risk, and would be more rational and might also help avoid needless and foolish tragedy arising from the enormous force of Nature.

Here is a tragic illustration. Consider an occasional but potentially serious UK hazard, namely windstorms. Falling trees pose a danger to people at home, pedestrians as well as motorists. Many UK residents sleep in homes overshadowed by tall trees that might cause grave property damage and human injury, should they be toppled by a very strong wind. The UK Meteorological Office provides advanced warning of the arrival of a dangerous storm and its potential consequences. However, neither the weather forecasting agency nor the government ministry it advises, ventures as far as to suggest to the public any specific mitigating action. Inevitably, some citizens, e.g. those sleeping in makeshift temporary homes under the shadow of a large tree, would be more vulnerable than others.

Tragically, during a severe windstorm that swept through southern England on the night of 27–28 October 2013, a 17 year-old schoolgirl, Bethany Freeman, was crushed to death after a tree fell on the caravan which was her temporary accommodation during the refurbishment of her permanent home. This tragedy raises an important issue about individual decision-making and willingness to pay to avoid a risk. Suppose the probability of the tree toppling onto the caravan during the night was P. If this were to happen, the contingent probability of an occupant being crushed to death was extremely high, close to one. How high would P need to be for the girl to consider alternative accommodation for just that night, e.g. staying with family, neighbors or friends?

According to the UK forestry commission, there are about 1.3 billion trees in England. In the 1987 UK windstorm, 15 million trees were felled, and several dozen people were killed. This was the most damaging UK windstorm in 300 years. In the strongest UK storm, there might have been about a 1 % chance of a specific tree being felled. The weather forecast on 28 October 2013 indicated that the impending storm would have been near-hurricane force, but not as severe as the 1987 storm. On the night of this storm, the chance of an individual tree being felled might have been estimated conservatively at 1/1000. This is the level at which anyone sleeping in a caravan under a tall tree might have been advised to find a safer abode. An optimistic estimate of the chance might have been of the order of 1/10,000. This is the level at which a highly risk-averse person might have thought of finding a safer abode than a caravan.

A small academic survey of European geoscientists and social scientists was undertaken by the author to gauge willingness to pay to avoid the danger posed by a falling tree which had a 1/1000 chance of toppling during a severe windstorm. Given the choice of sleeping in a static caravan under a tree or paying 50 euros to stay overnight in an inexpensive Bed and Breakfast, the latter was the consensus choice. This consensus remained when the choice was paying 200 euros for a night at an average city hotel—or even 500 euros for a luxury five-star hotel. This is consistent with basic cost-benefit analysis; 500,000 euros is well below the usual value of a statistical life in European economic studies. For the ill-fated schoolgirl, Bethany Freeman, even 50 euros might have been unaffordable without parental or other family assistance, but the option of staying overnight with a friend should have been feasible, as well as rational.

The challenge with involving citizens in the decision-making process is one of conveying to ordinary citizens a better understanding of the basic principles of chance and risk (see e.g. Woo 2011), so that their decisions are less affect-laden, dominated by their intuitive feeling of risk, and take account more of risk analytics. But Hendrickx et al. (1989) found that warnings are more effective when respondents are given narrative information expressed in scenarios and anecdotes rather than harm frequencies in bar charts and data tables. Identifying relevant scenarios and compelling anecdotes is thus an important aspect of public risk communication.

The tragic case of teenager Bethany Freeman provides both a readily comprehensible scenario and memorable anecdote to illustrate the cost-benefit aspects of hazard decision-making. A tree falling is a somewhat easier and more familiar agent of damage to conceptualize than a building collapse. Gaining a grasp of building vulnerability requires some level of understanding of the civil engineering of structures. By contrast, the likelihood of a tree falling in a very severe windstorm can be estimated statistically from past major windstorms, and visualized in terms of how many trees might fall within a village containing a thousand trees. The specific wind vulnerability of any tree is hard to gauge without arboreal expertise. In terms of weighing the relative costs and benefits of evasive action to avoid danger, the tree fall example is one of the simplest scenarios of the potential for cost-effective risk mitigation.

13.3.2 Nudging Behavior

Acting in accord with social evidence is a standard behavioral trait underpinning efforts made by corporations and governments at public persuasion. To answer the key public policy question how people can be helped to make good decisions for themselves, without a curtailment of freedom, economist Richard Thaler and lawyer Cass Sunstein (2008) have developed the nudge principle. Advocating a policy of libertarian paternalism, they have suggested ways in which people can be nudged, rather than coerced or obligated, to make decisions that serve their own long-term interests. There are informed and unintrusive ways of achieving this goal. But it takes enterprise and creativity to find viable solutions to the challenge of helping people to make good decisions for themselves.

The idea of nudging citizens to act in their own safety interest is popular with democratic governments espousing the principles of participatory politics, and happy to encourage each individual to take more responsibility for being his or her own decision maker when faced with important issues of health and safety, personal and financial well-being. Fire safety at home is a matter of universal concern, and governments may nudge citizens to install smoke alarms, but ultimately it is up to each UK household to decide on this. Similarly, to avoid elderly residents of poorly insulated homes from suffering hypothermia during a freezing winter, a government may nudge citizens to improve their loft insulation, perhaps with a grant or subsidy to cover part of the improvement cost.

13.4 The Precautionary Approach

Concern over looting is a common reason for reluctance to evacuate. The deployment of police patrols to deter post-evacuation looting was a nudging feature of the following case study to encourage mass evacuation. This relates to a European coastal storm surge crisis. The evacuation of several thousand homes on the Essex coast of Eastern England took place on the night of 5 December 2013, as the major European storm Xaver approached, generating extreme storm surge levels not witnessed in UK since the great 1953 coastal flood disaster, which claimed more than 300 English lives. This is a copybook example of the application of the precautionary approach to dealing with an emerging natural hazard crisis. There was no need or indeed time for public consultation over what to do. The local chief fire officer took firm control of public communication. This explained clearly the reason for the evacuation of the coastal town of Jaywick, its precautionary nature, and where its residents would be temporarily sheltered.

> The information that we have from the Environment Agency is that the water is going to be about half a meter from the top of the sea defenses, but obviously with some significant winds blowing there will be waves over the top of those defenses. The decision has been taken to evacuate Jaywick as best we can as a purely precautionary exercise and I would urge people not to panic. People will be evacuated to school buildings in the Clacton area. If people are able to voluntarily leave and stay with friends and relatives overnight that is always a good idea and will be very helpful. Police officers will be knocking on every door in the village and asking people to leave. We can’t force people to evacuate their homes, but as a purely precautionary exercise it would be sensible to do so.

The mandatory evacuation of a population segment in the presence of a highly uncertain hazard is a tough decision for any public authority to make, given the consequential disruption to life and commerce. The difficulty of the decision increases with the number of evacuees. Where the number is limited to a few thousand as above, the logistics of house-to-house warnings and the provision of temporary shelter are very much easier than if tens or hundreds of thousands of citizens are involved. The evacuation of Houston ahead of Hurricane Rita in September 2005 is a salutary example (Christian 2013).

Furthermore, the difficulty of a mandatory evacuation decision also escalates with the duration of an evacuation, in the event of a false alarm. For the residents of the coastal town of Jaywick, one night of rough sleeping in an inland school building would have been a small cost compared with the benefit of being kept safe from becoming a storm surge casualty.

The likelihood of the storm surge overtopping the sea defenses was in fact high enough for the evacuation to be justified purely on a cost-benefit basis, quite apart from the exercise of the precautionary principle. This is quite common in a crisis situation. The costs and benefits of a disruptive action, such as evacuation, may be crudely estimated. If the balance is tilted towards action, the precautionary principle can be readily invoked as an approval seal on the decision. By contrast, if the cost-benefit balance is tilted against action, it requires more boldness to invoke the precautionary principle, as the next European flood example shows.

Coastal storm surge is far easier to forecast than a flash flood, which can arise quite suddenly after a deluge of torrential rain. In Sardinia, on 24 November 2013, 17 lives were lost during flash floods which swept away bridges and flooded homes, and left the port city of Olba under water. The deaths sparked angry accusations that the island had not been sufficiently forewarned or prepared for the massive amount of 44 cm of rain that fell, which is about the annual rainfall in the island's capital city, Cagliari. To compound the disaster, emergency response was hampered by the incapacity of trucks of Sardinia's fire brigade which were marooned in flooded areas.

Compared with the extreme UK storm surge several weeks later, which could be anticipated by weather forecasters hours in advance, the meteorological forecast time for the severe Sardinian flash flood was very much shorter. Population safety might potentially have been enhanced with an earlier call for evacuation, but this call would then have had to have been made at a time when the likelihood of a severe flash flood was really still quite low. This early evacuation call might not therefore have been warranted by cost-benefit considerations, but might nevertheless have been made under the general safety umbrella of the precautionary principle. But this is a tough call to make because of the public recriminations following a false alarm.

13.4.1 Independence of Event Likelihood

The precautionary principle is a stalwart of crisis decision-making, provided that the disruption duration and cost are manageably finite both for the evacuees and the civil protection authorities. A key feature of this principle is its absolute sense of risk intolerance. Regardless of how small the hazard probability may be, (as long as it is ostensibly non-zero), the existence of a substantial casualty potential may be argument enough for the precautionary principle to be invoked and implemented to mitigate the risk. Citizens are not customarily involved in decisions invoking the precautionary principle in their safety interests. However, there are circumstances where the disruption caused to the lives of citizens may be so substantial as to cause some citizens to question the precautionary decisions made.

It is salutary to consider a further application of the precautionary principle to evacuation decision-making. The Iceland volcanic eruption of Eyjafjallajökull in April 2010 took European airport closure to a new dimension in hazard decision-making. In a hazard situation fraught with very high uncertainty, adoption of the precautionary principle by civil protection authorities can create an unacceptable level of economic disruption. For example, the precautionary principle applied to civil aviation required planes to fly around a volcanic ash cloud. But this is aeronautically impossible when an airport is enveloped by volcanic ash as was the case with Heathrow, when the Iceland volcano erupted in April 2010.

The persistence of the ash cloud for weeks forced airlines and their stranded frustrated passengers to question the precautionary principle that planes should never fly through any volcanic ash cloud. Indeed, the BA head, Willie Walsh, was on board the test plane that flew through the ash, so as to be able to reassure BA passengers that it was safe to fly. Under economic pressure from airlines, even though there was still a very small amount of ash in airspace, Heathrow re-opened. The decision risk was passed on to the airlines, and ultimately to passengers.

13.5 Rational, Equitable, and Defensible Safety Policy

Public safety is threatened by numerous natural and man-made hazards. Insights may be usefully gained by broadening the field of safety vision. Thus lessons on general rail safety principles are relevant to natural hazards, especially from countries where, for environmental and historical reasons, passenger safety poses a major challenge. As the Victorian pioneer of rail transport, Britain has the oldest railway system in the world. As with seismic retrofitting, it is easier to build in rail system safety starting afresh than improve the safety of an existing railway system.

For taking decisions in the British railway system, high-level principles have been developed (Rail Safety and Standards Board 2009). As with earthquake building codes, the legacy of past tragic British railway disasters has been to refine these key principles. The final stage of the decision-making framework is to ask the simple but testing question: ‘Does the decision make sense?’ Specifically, the decision must meet the following three fundamental goals:

- **Rational**, meaning that the decision has been taken for sound reasons and is not arbitrary.
- **Equitable**, meaning that due regard has been given to everyone’s interest.
- **Defensible**, meaning that it can be explained if challenged.

No decision pre-determines the outcome, which depends on myriad stochastic factors outside the control of the decision-maker. But irrespective of the outcome, every decision should make sense, and be rational, equitable and defensible. An explicit and transparent initiative to establish these criteria would be somewhat of a break with earthquake tradition. It has been usual during seismic crises for decisions to be entrusted to senior officials who would make their decisions in an authoritative executive style, based on their competence and experience. However, decisions may then be subjectively biased by an individual’s own personal sense of rationality, equitability and defensibility.

For any decision to qualify as being sound, it must involve considering both its advantages and disadvantages. Regrettably, many important decisions are made that fail to do this. Individual cognitive dissonance may hold sway, and the negative issues surrounding a decision may be conveniently swept aside and disregarded. Sound decisions must, therefore, weigh both the pros and the cons. For a decision not to be or seem arbitrary, there has to be a systematic, objective, and quantitative procedure for achieving a fair balance.

Quantitative risk assessment is one tool for facilitating rational decisions. This is recognized to be particularly useful where some comparison of risk before and after an intervention is required. However, qualitative risk analysis may also count as rational, where there is an abundance of relevant experience upon which risk is estimated. In respect of involving citizens in the decision-making process on engineering system safety, it has of course to be recognized that quantitative risk assessment is a tool with which only a small minority would be familiar, and that, furthermore, few citizens would have the competence or experience to give sound reasons for their judgements.

The need for a decision to be equitable lies at the very core of participatory decision-making. It is often far easier to arrive at a decision that suits the great majority, but not a small minority than to take due regard of everyone's interest. Here is where citizens have to be centrally involved, so that all views can be heard inclusively and given due regard in the ultimate decision-making process. This is far from being the normal case during seismic crises. Often decisions are made without consideration let alone representation from some interested parties. For a decision to be equitable, there has to be a solid element of participatory decision-making. In the crisis situation following a major earthquake, many challenging decisions will need to be made about evacuation from the region affected, and the timing of return to residences and businesses.

The population at risk is heterogeneous in many ways, not least in their sense of risk aversion and locus of control, and in the cost to them of avoiding or reducing risk exposure. To address this heterogeneity in an equitable manner, some degree of self-organization may be encouraged, with the practice of nudging citizens to act according to their own safety self-interest. Where mandatory evacuation action is decided, then special consideration should be given to those community members who may be old and frail, disabled or otherwise especially disadvantaged. In order to be seen as being equitable, additional assistance may need to be offered to the elderly and those with mobility difficulties.

The need for a decision to be defensible is clear from the prospect that a decision is open to challenge. If the reasoning behind a decision is unsound, the underlying weaknesses are liable to be found and exposed by media journalists or lawyers. Decisions need to be able to be explained cogently as and when they are challenged.

Transparency and accountability are key to decision defensibility. Decisions need to be explained properly to the public, unfettered by technical terminology and jargon, and unobscured by any scientific or technical black boxes. All recommendations that are made need to be supported by arguments that clearly balance, for all members of the public, the corresponding benefits against the costs. A prerequisite for a decision to be defensible is that adequate preparations were made to facilitate the decision when it had to be made. Decision preparedness is vital for decision effectiveness. It is difficult to defend a decision if there was inadequate preparation to make it. It would be a poor excuse to admit to lack of foresight in decision preparation, especially in respect of public participation.

13.5.1 Making the "Right" Decisions

Transparency and accountability are key to decision defensibility. Decisions need to be explained properly to the public, unfettered by technical terminology. There are numerous windstorm illustrations of the short-term application of the precautionary principle. For example, a precautionary approach to the risk of tree obstructions on railway tracks was taken by a number of UK rail companies in advance of the major windstorm that struck southern Britain on the night of 27–28 October 2013. Most regional rail services were cancelled well before it was known how severe the track problem was. The consequent economic disruption was massive: hundreds of thousands of commuters were delayed in getting to work the following day.

UK Prime Minister David Cameron queried whether train companies had overreacted by cancelling so many services during the windstorm. The Prime Minister refused to back many rail firms' decision to halt all services throughout the morning after the storm, simply saying it was important that all decisions were based upon good evidence. He said, '*Everyone has to act on the basis of the evidence that they are given. Obviously afterwards we will be able to look back and see whether people made the right decisions.*'

This statement by the highest democratic authority in the nation merits close scrutiny, because it raises key issues in decision-making on matters of public safety. As the UK Prime Minister said, everyone has to act on the basis of the evidence that they are given. According to the precautionary principle, if there is some evidence of a potential life-threatening threat, then action to avoid this threat would be justified. On the evening of 27 October 2013, there was clear meteorological evidence that wind gusts might develop capable of felling trees close to railway lines. Accordingly, several railway companies cancelled all services until the storm had passed. But what alternative decisions might have been made?

In principle, a small selective service might have been operable on those lines spared the worst wind gusts, and where early morning track inspection could verify that the lines were clear of obstruction, and therefore absolutely safe to re-open. Railway passengers were not consulted at all in the short-term closure decision. Participatory decision-making involving rail passengers would only happen routinely for long-term or permanent track closures. For those lines which could have been passed as safe before the peak morning commuting period, the passengers would undoubtedly have wished to have been able to travel. However, there would have been a significant logistical burden imposed on railway managers to be able to check that specific individual lines were safe. This raises the question as to how a 'right' decision might be defined.

Although there is inherent semantic ambiguity over what constitutes a 'right' decision, it is possible to claim that a decision is justified, not in any absolute philosophical sense, but according to an established principle that has been followed. Even if the quality of a decision is hard to gauge in an absolute sense, it may be possible to grade decisions in a relative sense. Consider the following generic decision situation. A decision-maker decides on an action A to mitigate the risk of casualties if hazardous event E were to happen. Before a judgement can be made on this decision, it is necessary to know what other actions B might have been taken, which would have been less economically disruptive than A, whilst still mitigating casualties to the same extent. In a strict formal mathematical sense, we could say that decision B is *superior* to another A if it achieves the same level of risk mitigation, but at lower cost.

In the above rail example, a decision to wait-and-see before cancelling all services would have been less economically disruptive, whilst not placing any passenger at risk. This might then be regarded as a superior decision to the blanket cancellation of services. The optimal decision would have been one which minimized the degree of passenger service disruption, whilst not exposing any passenger to risk from the windstorm. An example of this type of decision making for public transport is that adopted by airlines operating flights to and from Heathrow. Cancellation of flights was prioritized so as to minimize windstorm disruption to long-haul flights; short-haul passengers had other travel options.

Another related question is how decisions may be compared which have different risk mitigation effects. In a strict formal mathematical sense, we could say that decision B is *superior* to another A if it achieves a higher level of risk mitigation at the same economic cost. For example, there might be several alternative methods of track safety inspection, which are of equivalent cost, but one may be more effective and thorough at detecting dangerous track flaws than another.

13.6 Conclusions

There is a fundamental democratic principle that free citizens of a democratic state are entitled to have access to the best safety information available, and have the freedom to make their own choice in the best interests of themselves and their families. Even in mandatory evacuations, where staying behind may be against the law, some may stubbornly insist on remaining. It is rare for people to be forcibly removed from their homes, even if the chance of survival is very low, as with the approach of a large tornado or huge storm surge. Citizens who have defied evacuation orders sometimes cite their survival in previous extreme events, without reckoning on the greater threat posed by an imminent event.

In order for choices to be well informed by the information available and the uncertainty over threat level, the public needs to be better trained and educated about risk analytic issues, in particular basic notions of chance and uncertainty, so that judgments are less based on the intuitive subjective gut feeling of risk, and become more evidence-based and rational.

Rather than using its power and authority to direct and regulate the behavior of its citizens, a government may wish to encourage better individual choices by employing various explicit or implicit forms of behavioral nudge. Some government assurance or even financial warranty over the outcome of an operational forecasting action might be helpful in persuading some hesitant and reluctant citizens to take some mitigating actions, despite the large uncertainty. But, as with smoking, individuals retain the freedom to take risks as they please—up to a point. Having an absolute responsibility for the security of its citizens, governments may intervene to prevent people from taking unduly excessive risks. Much safety legislation, e.g. for road traffic, is based on this consideration, and is often introduced in the wake of some disastrous event which highlights the severity of a risk.

As an over-arching principle for the involvement of citizens, sound decisions made by civil protection authorities should be rational, equitable and defensible. A rational perspective is engrained in the framework of cost-benefit analysis, where the benefits of any risk mitigation are weighed against the costs. But qualitative risk assessment may suffice in circumstances where there is an abundance of experience.

In respect of citizen involvement, it is not sufficient in itself for a decision to be rational. As an outcome from rational evidence-based risk analysis, no sector of the population should feel disrespected or disregarded by civil protection authority actions that may be perceived as inequitable. Participatory decision making is essential to ensure that solutions reached by civic authorities are equitable. Guidelines for the involvement of citizens in decision making must pay due regard to the need for fairness. The involvement of citizens cannot be restricted to some self-selected body of concerned citizens, nor even a specially appointed group of citizens, however well qualified. Future ideas for increasing citizen involvement should recognize and take advantage of the expanding importance of social media as a universal efficient platform for crowdsourcing, disseminating information and facilitating the rapid public exchange of views and opinions.

And lastly, all decisions involving some citizen participation should be defensible against queries by the media, public or members of the legal profession. Involvement of citizens in the decision making process should help ensure that no decisions are made which are indefensible in a court of law or even in the social media court of public opinion.

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Chapter 14
The Natech: Right-to-Know as Space-Time Puzzle

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Abstract Federal environmental law began with a plea: that agencies and other parties consider, and mitigate, the environmental impacts of their work. The task remains unfulfilled given the nature of those impacts: They feature system effects, nonlinear interactions, feedback loops, discontinuous and threshold dynamics, and uncertain boundaries. The administrative state has limited means to address them. It relies on artificial constructs to assess and respond to impacts, such as worst-case scenarios, reasonable foreseeability, and scales that are either inappropriately narrow (“linked” projects) or large and vague (“program-level”). Right-to-know laws share this shortcoming, a product of the disasters that led to their enactment and the laws to which they were appended. In place for a quarter century, the framework is under renewed scrutiny. Recent accidents reveal risks from new and repurposed infrastructure, and point to chemical listing, threshold, labeling, and other potential reforms. But these are incremental adjustments to a baseline approach to chemical risk that operates under longstanding temporal and spatial constraints. Right-to-know privileges annualized data and the state of knowledge shortly after a release beyond a facility boundary. These choices limit data available for emergency response, particularly when chemical processing, oil and gas production, and other infrastructure are placed under stress. To explore how right-to-know laws can better account for system effects, I focus not on the black swan events or worst-case scenarios that shape new legislation and consume an outsized portion of administrative resources, but rather on increasingly common, geographically dispersed, and temporally discontinuous infrastructure stressors known as natechs. A natech event occurs when a natural hazard such as a storm, earthquake, or flood triggers technological accidents that result in the release of chemical agents into the environment. Natechs share several traits, including simultaneous releases, cascading and domino effects, and scattered or inaccessible infrastructure. They often occur under “best case” conditions, due to the weakness of the natural hazard trigger or the readiness of infrastructure in its path. They lead to non-state responses that identify, reconstruct, and track cumulative impacts that would be lost to regularized reporting at discrete scales. These non-state responses ensure situational awareness in emergent spaces, irrespective of facility boundary.

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And they suggest event sequences that can be leveraged for hazard mitigation. By focusing on a growing inventory of mundane infrastructure stressors, natechs can serve as proxies for some of the cumulative, delayed, distributed, and nonlinear impacts that environmental laws find difficult to address.

14.1 Introduction

West. Lac-Mégantic. Mayflower. Elk River. Faulty brakes and wires. Cracks in vintage pipes and tank cars. Banned substances and fuels rich in hydrocarbons. A breach of system integrity links once-silent infrastructure to altered landscape through bursts of entropy. In the wake of each accident, a parade of errors populates safety board and investigative reports. An explosion at the Adair Grain fertilizer storage facility erases the center of West, Texas. Alleged root causes pile up as agencies jostle for control of the site. Among them: limited oversight, process safety exemptions, failure to adopt voluntary codes, opposition to inherently safer design, and stalled efforts to ban ammonium nitrate in fertilizer (U.S. Chemical Safety Board 2014). In Lac-Mégantic, Quebec, tanker cars explode like a mushroom cloud, release a wave of crude oil into a river, lake, and storm sewers, and burn for 2 days. An array of errors is unearthed. Faulty brake application. Single-commodity freight. Tanker cars prone to rupture (Nicholson 2014). Theories of tight coupling, incubation periods, and the hallmarks of "normal" accidents lend order and sequence to these concerns (Perrow 1999). They are dutifully applied to discrete structures in disparate towns.

Sometimes the events reach a threshold, and our meager theories hit a wall. What happens is too large, unexpected, public, or costly to be considered an accident. Past experience does not account for what happened. There is too much loss. Rips appear in social fabric. A community copes not with an accident, but a disaster. The boundary that separates the two is blurry. Classic definitions pair human error with chance events (accident) and severe losses with a disruption in social structure (disaster) (Tierney 2007). As we cross the threshold, the differences are clear—scale, social resonance, sense of shock. The events of 3.11 at the Fukushima Daiichi complex in Japan provide an example: a tsunami claims the lives of 20,000 people and leads to three meltdowns that bathe an area in the radiation of untold Hiroshimas (National Diet of Japan 2012). Hurricanes Katrina and Rita are another: hazardous material spills from industrial facilities, onshore storage, and offshore oil and gas terminals in the Gulf of Mexico rival the Exxon *Valdez* spill (U.S. Senate Committee on Homeland Security and Government Affairs 2006). The lessons are broader but no less incomplete. Man-made disasters such as Fukushima and Katrina remain open-ended for some time, in terms of systemic causes and competing narratives wielded in their aftermath (Samuels 2013). Yet they encourage dramatic change, long before the narratives, and their implications for environmental health and safety, are sorted.

One such change occurred after twin chemical releases in Bhopal, India and Institute, West Virginia in the mid-1980s (Abrams and Ward 1990). Congress passed Title III of the Superfund Amendments Reauthorization Act, known as the Emergency Planning and Community Right-to-Know Act (EPCRA) (Emergency Planning and Community Right-to-Know Act 1986). EPCRA upgraded "right-to-know" obligations lodged in statutes such as the Freedom of Information Act (FOIA) 20 years earlier. EPCRA offered a community right-to-know—a "chemical FOIA that applies to the private sector" (Reitze 2005). The changes were sweeping. Among them, EPCRA required owners and operators of facilities to report inventories and releases of certain hazardous substances, and state and local governments to engage in emergency planning (Roesler 2012). EPCRA was drafted in response to disasters such as the methyl isocyanate gas leak at a Union Carbide facility in Bhopal that killed 2500 people and injured tens of thousands. Lawmakers mined industry and voluntary initiatives crafted in the immediate aftermath of Bhopal (Belke and Dietrich 2005). They amended CERCLA, a statute designed to limit exposure to hazardous substances over long time horizons (e.g., lifetime cancer risk) (Comprehensive Environmental Response, Compensation and Liability Act 1980). An extension of this framework, EPCRA offers a specific vision of environmental right-to-know, aimed at acute health effects from short-term exposure to chemicals (as during a major release), and long-term exposure to an inventory of toxic emissions (as is a concern near remediated Superfund sites). Other statutes augment the framework. EPCRA-sponsored databases, such as the Accidental Release Information Program, further expanded right-to-know. EPCRA requirements were linked to off-site consequence analysis, process safety standards, risk management plans, and other innovations by 1990.

Recent storage, railway, and pipeline accidents point to the framework's limited ability to prevent accidents or encourage appropriate emergency response. But the accounts adhere to right-to-know as defined a quarter century ago. They focus on gaps in the framework itself or as applied: statutory coverage, exemptions from chemical reporting, the capacity or discretion of emergency planners. The Elk River chemical spill, for example, is described as classic regulatory commons (Buzbee 2003). A coal washing solvent, MCHM leaks from an aboveground storage tank into a West Virginia river, placing the integrity of a water supply at risk for several hundred thousand. The solvent slipped through reporting and risk assessment requirements (Cooper 2014; Corona Environmental Consulting LLC 2014; Manuel 2014). Statutes such as the Clean Air Act do not list MCHM as a hazardous substance. Nor is it considered hazardous waste under the Resource Conservation and Recovery Act. The Toxic Substances Control Act grandfathers the chemical; EPA does not require data collection about its human health effects. It is not a high-volume chemical, meaning even voluntary tests by the manufacturer are not encouraged. It is a hazardous substance under the Occupational Safety and Health Act (OSHA), which triggers Material Safety Data Sheet (MSDS) requirements, which prompts reporting duties under EPCRA. But a local emergency planning committee (LEPC) did not prepare a response plan for the chemical spill and did not share information about chemical storage with first responders. Months after the release, the public continued to lack access to basic health data, including whether MCHM converted to other compounds after it breached the storage tank, presenting additional health risks (Cooper 2014; Corona Environmental Consulting LLC 2014).

The regulatory commons as right-to-know barrier rears its head again in accounts of West, Texas (Kaelin 2014; Weeks 2014; Frost 2013). West Fertilizer Company produced anhydrous ammonia. The quantity and reactivity of ammonium nitrate stored on-site escaped federal and state scrutiny. Process safety management under OSHA does not cover reactive hazards. The facility's risk management plan, submitted to EPA 3 years prior, did not have to address the substance's explosive risks. Local emergency response planners did not report the storage of tons of ammonium nitrate to first responders, as required under EPCRA. Part of the concern with local planners is statutory—EPCRA limits their authority to conduct on-site inspections (Reynolds 2013a). Data sharing was also strained among state and federal agencies, including the Texas Department of Environmental Quality, EPA, and the Department of Homeland Security (Reynolds 2013b). State law did not require monitoring of the storage facility, which may have begun to correct for these planning and reporting oversights. Failure to list chemicals, inspect facilities, and share data, the result of regulatory gaps and discretionary restraint, repeat in accounts of rail car and pipeline ruptures. Shale oil carried by rail through Lac-Mégantic was more explosive than labeled. The Bakken oil was highly volatile; tests and efforts to characterize it for safe transport were ongoing. Inspections were among the strained resources that had to be targeted based on past incident data, rather than new risks. First responders lacked information about the contents of tanker cars, despite required disclosure and labeling (Frittelli et al. 2014). Again, the concerns relate to environmental right-to-know as embodied in statute between 1986 and 1990.

Less clear is the framework's inability to police what many of these accidents represent: systemic risks posed by new or repurposed infrastructure. Consider the rise of unconventional energy such as shale gas, tight oil, and coal bed methane in the United States. The debate over human health risks and disclosure requirements for extreme energy production centers on a well stimulation technique, hydraulic fracturing, that occurs over brief periods of time at tens of thousands of wells in more than 30 states (Merrill and Schizer 2013). But the lifecycle of a productive well, which spans 20–30 years, is supported by an infrastructure that sprawls across vast plains and mountain desert terrain (Shonkoff et al. 2014). A drive along I-70 from Denver to Grand Junction reveals such infrastructure: well pads, pipelines, separators, compressor stations, heater treaters, glycol dehydrators, condensate storage tanks, evaporation pits, and other structures, some alien to the landscape, others repurposed or used in novel combination. Much of the infrastructure is unseen. For example, deepwater oil and gas production in the Gulf of Mexico relies on massive underground canyons (salt domes) to store natural gas, ethylene, and oil, as well as a maze of underground pipelines. A 25,000-mile network of underwater oil and natural gas pipes in the Gulf is submerged through marshes, swamps, and shorelines. On a map, it resembles a thriving city (Misrach and Orff 2013).

The infrastructure carries acute and chronic health risks that do not neatly align with right-to-know mechanisms for reporting and response. Because EPCRA does not preempt state law, approximately two thirds of the states with unconventional oil and gas (UOG) activity now have their own disclosure rules to augment the federal floor for the industry (McFeeley 2014). Their focus is chemical identification after a process is completed, rather than data sharing with landowners or emergency responders prior to hydraulic fracturing or in response to an accident. As for the toxins, fluids, and wastes (fugitive chemicals, drill cuttings, produced water, condensate, TENORM) emitted from equipment on a well pad, released further afield, stored and flashed from pits and tanks, or injected into the ground (Adgate et al. 2014), state and federal reporting, risk assessment, and response planning fall short (Gosman 2013). This would be true even if we tended to the framework's gaps as applied to UOG owners and operators: Reporting exemptions for UOG facilities (42 U.S.C. § 11023 (b)(1)(A)). Hazardous chemical reporting thresholds (e.g., 10,000 pounds of a chemical located on-site at any time) that fail to implicate equipment strewn across UOG fields (42 U.S.C. § 11002(a)(2); 42 U.S.C. § 11004(a)(1), (a)(2)(B), (b)(1); 42 U.S.C. §§ 11021–11022; 42 U.S.C. § 11023(F)(1)(A)). Constituents of drilling and fracturing fluids tallied separately for whether they meet reporting thresholds (42 U.S.C. § 11021(a)(3); 42 U.S.C. § 11022(a)(3)). Material Safety Data Sheets and Tier II forms that lack specificity and are riddled with trade secret redactions (Colborn 2011). To be clear, adjustments to any of these provisions would improve right-to-know. But they are incremental changes to a baseline approach to chemical risks in space and time, one that is not designed to address system effects and the risks they pose. Even under normal operating conditions, we have limited knowledge of the hazards presented by systems such as UOG infrastructure. A recent summary of the state of the art concluded that the systems introduce "indeterminate public health hazard[s]" to local communities (Agency for Toxic Substances and Disease Registry 2010). By ignoring how these systems deviate from normal conditions when stressed, right-to-know only builds on that ignorance.

System effects such as those introduced by UOG infrastructure are not only a problem for environmental right-to-know. They plague the broader project of disclosure and encouraging parties to consider the environmental impacts of their decision-making that began with the National Environmental Policy Act (NEPA). A chief critique of NEPA concerns whether environmental impact statements (EISs) assess risks in their proper context, including the linked and cumulative effects of projects (Karkkainen 2002). The proper scope of major federal actions—their impacts in space and time—continues to bedevil project planners. One response is to devote personnel and analytic resources to the "worst-case" scenario for a project, which was required for some time under the NEPA process and is now referred to as a "reasonably foreseeable significant adverse impact" (Bardach and Pugliaresi 1977). The worst-case is also a key component of EPCRA-style planning, a required off-site consequence in risk management plans under the Clean Air Act (U.S. Environmental Protection Agency 2004). But the documents are only as complete as the reported data upon which adverse impact estimates are built.

The required data, demanded after high-profile disasters and appended to occupational health and waste management statutes, speak to acute and lifetime risks. As with single-media statutes such as the Clean Air Act and Clean Water Act (CWA), the data are not designed to characterize risks posed by complex systems such as UOG infrastructure.

Right-to-know cannot evolve solely through listing, threshold, data transfer, and other gap-filling tactics identified after accidents. Nor should it await the next Bhopal to marshal support for an entirely new approach, and build artificial worst-case scaffolds around existing data in the meantime. We already have access to a growing inventory of best case, near miss, and other more mundane infrastructure stressors from which environmental right-to-know can be improved. The stressors are natural hazards—the floods, storms, winds, fires, and seismic activity that threaten infrastructure, trigger chemical releases, reveal unique efforts to bridge and fill gaps in data, and then recede into oceans, atmosphere, and substrate. Whether viewed in isolation or collectively, these "natech" events offer a third way for right-to-know reform, one attuned to the unique spatial and temporal elements of infrastructure risk.

14.2 The Nature of Environmental Right-to-Know

As "sub-canonical" environmental law, divorced from the media-specific focus of many statutes, EPCRA was a dramatic success (Aagaard 2014). Its most celebrated provisions, such as the Toxics Release Inventory (TRI), are loosely embedded in the environmental canon—they do not link directly to command-and-control structures in the CAA, CWA, and other statutes (Van den Burg 2004). They regulate by other means, most notably, by disclosure. Owners and operators of facilities that meet certain thresholds—ten or more full-time employees, 10,000 or 25,000 pounds of a listed chemical used or processed per year—prepare and submit reports that detail chemical releases (EPCRA § 313, 42 U.S.C. § 11023). EPA makes the annualized data public, with minimal processing. At first, there was little effort to translate toxics release data into exposure or other more useful human health information. Third parties assumed this responsibility, and learned how to make the data contextual and user-friendly (Fung and O'Rourke 2000). Environmental Defense's Scorecard web site is an example. It linked TRI data to fate and transport models and toxicological evidence, giving spatial context to the data through facility rankings and community-specific summaries (Scorecard: The pollution information site 2011). Congress and EPA followed suit. They expanded TRI's coverage to include waste management, source reduction, and persistent bioaccumulative chemicals (Roesler 2012). Aggregate emissions of listed toxins declined. Scholars argued that the decline was encouraged by the nature of data disclosed. Among EPCRA's innovations were metrics that could be easily aggregated, compared among facilities, and used for self-regulation by industrial hygienists and managers (Karkkainen 2001). EPCRA's success is impressive, in light of the fact that the statute is the last of six laws from 1972 to 1986 to require environmental disclosure.

Less storied are the broader provisions of EPCRA and related right-to-know laws, which are more ambitious. In the wake of Bhopal and Institute, EPCRA was the first federal law to require facilities to prepare response plans for industrial accidents. The emergency-planning mandate is developed in Sections 301, 303, and 304 of the statute. Section 301 requires states to set up emergency response committees (SERCs), divide territory into emergency response districts, and establish a local emergency planning committee (LEPC) for each district (42 U.S.C. § 11001). Section 303 sketches LEPC roles—organizing facility emergency plans and chemical inventories, creating evacuation plans and warning systems (42 U.S.C. § 11003). Section 304 concerns emergency reporting. An accidental release of an extremely hazardous substance (listed according to Section 302) above a reportable quantity triggers notification requirements, including quantity released, duration of release, medium of release, and potential risks. An owner or operator of a covered facility must report the release to the appropriate SERC and LEPC and first responders (42 U.S.C. § 11004).

EPCRA's planning mandate must be considered along with its disclosure program (set forth in Sections 311 through 313), as well as other laws that shore up EPCRA data sharing. Sections 311 and 312 give an example of how EPCRA leverages other statutes. The Occupational Safety and Health Act (OSHA) requires facilities to prepare a Material Safety Data Sheet (MSDS) for certain hazardous chemicals (29 C.F.R. § 1910.1200(g)(8)). Under Section 311 of EPCRA, the facilities must send the MSDS to the relevant SERC, LEPC, and fire department (42 U.S.C. § 11021(a)(1)). Section 312 details tiers (Tier I and Tier II) of chemical inventory data submitted to these agencies. Tier I includes the maximum and average daily amounts of the chemical present at the facility during a calendar year. Tier II facilitates emergency planning and is required in most states. It includes Tier I data as well as descriptions of chemical hazards, storage techniques, and location of chemicals on-site (42 U.S.C. § 11022). Other laws leverage EPCRA to build environmental right-to-know. Sections 304 and 112(r) of the Clean Air Act Amendments were drafted based on a review of emergency response requirements under EPCRA. Section 304 calls upon OSHA to issue emergency response regulations. OSHA, in turn, introduced a Process Safety Management (PSM) standard for hazardous chemical facilities (42 U.S.C. § 7404). Section 112(r) of CAA outlines a Risk Management Program (RMP) to supplement PSM with standard operating procedures, training, mechanical integrity, and process hazard controls (42 U.S.C. § 7412(r)). In addition, facilities conduct offsite consequence analysis and develop release scenarios, which include a worst-case release of the largest quantity of a substance from a vessel or process (U.S. Environmental Protection Agency 2013). The framework was in place by the early 1990s.

Much attention is devoted to the framework's retrenchment in an age of information security. Reports immediately prior to and after 9/11 likened chemical facilities to WMDs and showed that worst-case accidents could affect thousands (Schierow 2004). RMP and other data were pulled from libraries and web sites

(Babcock 2007). The discussion misses how even as an ideal type, environmental right-to-know can strain and falter under its own weight in certain circumstances. This is true when the twin goals of EPCRA—informing the public and enabling response—are pitted against infrastructure risks. Recent accidents hint at new risks for which the framework is ill prepared. A common tanker car filled with novel cargo. A pipeline moving dirty mixtures that prove impossible to clean. Fixed facilities subject to new stocks and flows. To address these risks in isolation is to better align EPCRA and related statutes with new risks. But threshold, chemical listing, data sharing, and other adjustments simply free right-to-know to work as conceived a quarter century ago. There remain two major conflicts between risks posed by unconventional infrastructure (such as the spread of chemical processing, once neatly bounded by fencelines, across rural and urban fields) and the right-to-know framework of old.

The first conflict is temporal. Chemical release reporting under EPCRA and related statutes occurs at two scales, annually and "immediately." Operators submit annual data, subject to thresholds and penalties. Some thresholds change according to the chemical in use or storage. Facilities also report the release of a hazardous substance (according to CERCLA) or extremely hazardous substance (listed under EPCRA) to the National Response Center (NRC) or appropriate emergency planning committees, subject to quantity thresholds (42 U.S.C. § 9603(a); 42 U.S.C. § 11004(b)(1)). Reporting must occur "immediately" (42 U.S.C. § 9603(a); 42 U.S.C. § 11004(a)–(b)). Emergency notification under EPCRA is more inclusive than the statute's inventory provisions. It concerns a greater range of chemicals and avoids the petroleum exclusion that limits TRI's application to oil and gas. What must be reported is standard: chemical names and listing information, an estimate of quantity released, time and duration of the release, medium into which a release occurred, acute or chronic anticipated health risks, and precautions to take because of the release and a point of contact for further information (42 U.S.C. § 11004(b)(2)). When to alert the NRC or planning committees is less clear. For example, CAA regulations call for "prompt" reporting of deviations from permit conditions, including a facility's startup, shutdown, and malfunction plan. In practice, this means 2 working days (40 C.F.R. § 70.6(a)(3)(iii)(B), 70.6(g)(3)(iv)). Noncompliance with a permit under CWA that may endanger health or environment must be reported within 24 h (40 C.F.R. § 122.41(I)(6)). A hazardous materials release along a highway must be reported within 12 h (49 C.F.R. § 171.15(a)). But the term used to describe emergency release notification under EPCRA and CERCLA is "immediate." EPA interprets "immediate" to mean within 15 min of actual or constructive knowledge of a release (Environmental Protection Agency 1999). The statutes also include follow-up reporting. For example, under EPCRA, owners or operators submit a follow-up emergency notice "as soon as practicable," or within 30 days of a release according to EPA policy (42 U.S.C. § 11004(c)). Each statute aims for its own version of near real-time reporting. But between perfunctory reports, often minutes after a release, and data provided for annual consumption, much can, and does, occur when the subject is industry prone to infrastructure risk.

Beyond the temporal conflicts, emergency reporting is spatially limited. This is true even when reporting thresholds—quantity of chemicals used or stored in a calendar year, reportable quantity of a listed substance—are met by a release. EPCRA applies to "facilities," which is significant for three reasons (42 U.S.C. § 11004(a)–(b)). First, a release must travel beyond a facility boundary to trigger reporting. This is also a requirement under CERCLA, where a release "from" a facility prompts immediate reporting to the National Response Center (42 U.S.C. § 9603(a)). Second, "facility" means "all buildings, equipment," and other structures on a "single site," or adjacent or contiguous sites when there is common ownership (42 U.S.C. § 11049(4)). This definition expands the reach of the boundary beyond which a release must travel before a reporting requirement is triggered, to all structures present at an entire complex. At the same time, it complicates whether releases at contiguous sites lacking common ownership, but that together exceed reportable quantities, will be reported. Third, the release must be from a facility "at which a hazardous chemical is produced, used, or stored" (42 U.S.C. § 11004(a)). This means that the facility must meet a threshold quantity for production, use, or storage of the released chemical. In the chaos of a hazard affecting a coastline, floodplain, or other region, hazardous chemicals that move through or come to rest on non-threshold facilities do not implicate those sites in reporting requirements. This further limits our ability to track chemical releases across anything beyond discrete parcels of land.

Environmental right-to-know prioritizes annualized data and the state of knowledge immediately after a release beyond a facility boundary. Notable efforts persist to improve performance at these scales. But to promote safety and resilience within the nation's UOG fields and other infrastructure, the right-to-know mandate is due a more foundational overhaul. To parse what those changes might look like, we do not turn to the high profile, worst-case chemical releases that usher in EPCRA and other laws. Instead, we consider a larger and more varied class of release, the "natech" (Young et al. 2004). Natechs occur when natural hazards trigger technological accidents that result in the release of chemicals into the environment. Unlike the canonical chemical release under acute (accident) or normal (annual) conditions from a discrete unit or structure, natech events stress entire infrastructures. They offer a growing inventory of unique spatial and temporal risks that must be a focus of next-generation response and hazard mitigation.

14.3 Natech Near Misses

The literature on natechs concerns natural hazards that lead to chemical releases from man-made structures (Krausmann et al. 2011). It is punctuated by case studies of high-profile disasters such as the Northridge earthquake or the post-Katrina impact of chemical releases 10 years later (Lindell and Perry 1997). The first attention to off-site, community consequences of a chemical release after a natural hazard concerned the cascading impacts of an earthquake on 21 facilities in

Kocaeli, Turkey in 1999 (Steinberg and Cruz 2004). Katrina is a notably diverse natech. After the levees failed, floodwaters inundated the city with industrial chemicals, mold spores and endotoxins from contaminated sediment aerosolized as the waters receded, and a large refinery spill persisted, among other events (Cruz and Krausmann 2009). Three-dozen studies of post-Katrina chemical releases failed to determine even the number of releases at issue. But for every Kocaeli or Katrina, there are hundreds of failures of infrastructure caused by external, natural triggers that are not the subject of sustained root cause analysis. These natechs are not black swan events; they are regular, even "best case" external stressors of UOG and other infrastructure. Sustained study of these interactions reveals patterns and sequences that can inform the spatial and temporal shortcomings of right-to-know.

Despite the growing number of natech events, our knowledge of their scope and frequency remains limited. Major studies of the prevalence of natechs are completed roughly every few years (Showalter and Myers 1994). For example, Sengul et al. (2012) reviewed entries in the National Response Center's Incident Reporting Information System (IRIS) and other databases. IRIS compiles hazardous substance releases reported under CWA and CERCLA, petroleum releases that violate water quality standards, and hazardous materials incidents regulated by the Department of Transportation. The aim of this study was to characterize natech events in the United States between 1990 and 2008. The databases were beset by incomplete, duplicate, and missing records, and relied on self-reporting by responsible parties under relevant statute. Each entry revealed a state of knowledge shortly after a chemical release. Otherwise, data on hazardous or extremely hazardous substances were often not reported (they were below reporting thresholds), difficult to reconstruct with existing databases, or lost. The "incident cause" field in a database such as IRIS does not encourage root cause analysis—there is usually no detailed information on equipment failure mode or trigger (e.g., wind speed, height of floodwater). Despite these challenges, the authors were able to remove redundant entries, scrub the data, and supplement it with facility-specific information. Similar data heroics were made in prior estimates of natech prevalence. The authors found an increase in the number of natechs in the United States from about 600 in 1990 to 1900 in 2008 (16,600 during the study period). Natural hazard triggers included (in order of frequency) earthquakes, hurricanes, floods, lightning, winds, and storms (Sengul et al. 2012).

Data sufficient to characterize the natechs that can be identified are in even shorter supply. Yet natechs offer a record of increasingly common, geographically dispersed, and temporally stretched stressors of chemical processing, storage, and transport. Often the record entries represent the kind of best case or near miss scenarios that fail to capture the imagination or usher in regulatory change. But they invite further cause and consequence analysis and suggest important avenues for reform. From infrequent inventories in the published literature, we learn that natechs share several traits (Steinberg et al. 2008). They present multiple, simultaneous releases to already overburdened first responders. Response occurs under suboptimal conditions, with water, power, communications and other resources knocked offline. Damaged facilities are rendered inaccessible by the natural hazard.

Domino and other cascading impacts are common within and beyond the fenceline, defying pre-release fault tree analysis. The types and amounts of materials released are often unknown or unreported. In this section, I explain how these characteristics were at work during two "best case" impacts of natural hazards on oil and gas infrastructure. In the next section, I discuss how environmental right-to-know might better respond to these challenges.

A best-case natech scenario may concern either the weakness of its natural hazard trigger, or the readiness of the chemical infrastructure in its path. Our first example is Hurricane Isaac, which made landfall along the Gulf of Mexico in August 2012 (Hurricane Isaac Batters Gulf Coast Industry 2012). Oil and gas refining and chemical processing infrastructure is often found in low-lying regions such as the Gulf, where it is subject to coastal flooding, storm surges, and sea level rise. Isaac was a predictable, Category 1 hurricane, the weakest by wind speed to move ashore in over 50 years. Despite advanced warning and tracking, the routine storm resulted in widespread pollution from oil and gas infrastructure. By mid-September, 130 accidents were reported to the National Response Center that could be directly attributed to the hurricane. An additional 69 reports were possibly related to the storm, given the dates and incident types involved. Of the 130 reports, 108 listed specific pollutants that were either released or suspected. Combined releases within the chemical corridor equaled roughly 12.9 million gallons plus 192 tons of gases, including sizable quantities of known carcinogens (Gulf Monitoring Consortium 2012).

We find each of the hallmarks of a natech in Isaac's breach of the Gulf Coast. Multiple, simultaneous releases affected a range of structures between late August and mid-September: a chemical storage and transfer terminal, a chemical plant, refineries, coal terminals, and marshland and offshore sites that suggested improperly shut down wells, pipeline leaks, and residual contamination from the Deepwater Horizon spill, among others. Some infrastructure remained inaccessible for much of the reporting period, including a flooded terminal and offshore locations. Initial reporting proved inaccurate. For example, the Stolthaven terminal's initial report, based on a pre-storm inventory, did not include several hazardous substances that were released. There were numerous on-site and domino impacts of infrastructure. For example, levee failures flooded facilities and allowed contaminated water to spill into various bodies. Limited storage capacity resulted in untreated wastewater runoff to Lake Maurepas. Tank hatches, floating roofs, and railroad tanker cars were upset by wind and floodwaters, leading to further offsite consequences. Owners and operators of infrastructure along Isaac's path exhibited a range of behaviors. For example, the Motiva Norco refinery chose not to shut down as Isaac approached. It released 27 tons of volatile compounds and nearly 1 ton of benzene during an unexpected shutdown and restart as the storm moved through the area. Flooded compressors and failure to keep flares lit in high winds contributed to the shutdown. The Exxon Chalmette Refinery did implement advanced shutdown procedures, but faulty pollution controls led to an unexpected release of 58 tons of sulfur dioxide. Untreated, contaminated stormwater runoff was common due to limited pre-storm storage capacity and post-storm floodwater pumping into lakes, wetlands, a canal, and other waters. Among the chemical notifications filed, 45 did not include spill estimates (Gulf Monitoring Consortium 2012).

Our second "best case" example concerns the readiness of infrastructure rather than the strength of the natural hazard trigger. The Front Range, which spreads east from the Rocky Mountains in Colorado, is one of several oil and gas centers in the state. Weld County alone has over 20,850 active oil and gas wells in a low-lying basin, where floodwaters converged in 2013 (Colorado Oil and Gas Conservation Commission 2014). Prior to the flood, split ownership, a lack of riparian setback requirements, and geological considerations gradually moved many of the wells—nearly 6000—to within 500 ft of a named water body. Approximately 2650 of the wells were ultimately within the flood impact zone. The flood was severe in terms of the quantity and scope of floodwaters and pre-storm conditions (e.g., dry weather), although it did not approach historic peak flows (5000 versus 11,000 cubic feet per second). But the natural hazard affected best-case oil and gas infrastructure (Colorado Oil and Gas Conservation Commission 2014). Open, earthen pits for produced water and condensate storage were rarely used, even though operators in Weld County held 3200 permits for their use. Most of the wastes, in addition to drilling and fracturing fluids, were stored in closed tanks. By comparison, UOG firms along the Western Slope of the state make frequent use of open storage. In addition, lower energy prices suppressed pre-storm UOG activity in the region. Immediately prior to the floods, there were no active hydraulic fracturing operations in Weld County. Nor were any wells under active drilling or preparation. Advanced warning was sufficient to give operators the chance to trigger automatic shut-in at these wells. The Colorado Oil and Gas Association, an industry group, estimated that 1800 wells were shut-in. Yet the hallmarks of a natech emerged as floodwaters inundated the region.

UOG fields suffered substantial damage, to well pads, wellhead structures, tank batteries, separators, heater treaters, and other production equipment (Colorado Oil and Gas Conservation Commission 2014). There were three primary causes for the damage: water rushing past infrastructure, impacts from large debris, and rising groundwater. Each resulted in chemical releases—oil, condensate, and produced water among them. The floodwaters interacted in unexpected ways, causing lateral stream movement and rechanneling. Domino impacts were reported as loose equipment moved within and across well pads. Access problems due to the flood and stretched resources (including only about a dozen inspectors for thousands of oil and gas wells) limited the state's ability to characterize the extent of the spills. COGCC's attempts to track leaks and other releases were "hampered by wet and slow-going conditions" (Colorado Oil and Gas Conservation Commission 2014). Residual water and damaged roads rendered many well pads inaccessible. By March of the following year, COGCC made its way to a portion of the wells in the floodplain (3400) to publish estimates of chemical spills. While most wellheads were taken off-line pre-flood, some owned by smaller companies lacked remote shut-in capability. Had they been damaged—by higher water flows, domino or other impacts, or simply by random movement of the floodwaters—"hard-to-control spills likely would have occurred" (Colorado Oil and Gas Conservation

Commission 2014). During the floods, COGCC focused on two emergency response tasks: achieving situational awareness through contacts with industry, and sharing information with the public. Much of the data, including chemical releases, had a single origin: owner and operator efforts to assemble inventories of chemical use and storage at well pads immediately prior to the floods (Colorado Oil and Gas Conservation Commission 2014). There remain concerns about unreported releases, particularly from subsurface flow, gathering, and other pipelines (Interview with Executive Director, Fractivist, in Fort Collins, Colorado 2014).

Conditions on the ground after even best case natechs reveal the limits of right-to-know. Reporting-by-facility strains to account for regional or domino impacts. Immediate and annual reporting bookend more pressing attempts—spanning weeks or months—to access sites and better inventory chemical releases. These efforts make use of limited source material. Absent from the source material are releases that are unknown across a region, non-threshold given the amount released or facility where they come to rest, or hidden within facility boundaries that they fail to breach. The chemical releases are distributed in space and time, over watersheds and coastal regions and continuing long after they trigger initial hazardous substance notifications. More than one technological accident occurs, simultaneously and discontinuously. Some are cascading events, which link failed equipment or breached infrastructure at one site to a release or deposition at another. Site access is restricted or limited, and mitigation measures can be disrupted by the natural hazard. In turn, hazardous chemical data are either not reported (they are below reporting thresholds), or lost (due to access and other limits to operator or first responder ability to detect), or difficult to reconstruct with existing databases. At the same time, responses to flash floods, coastal impacts, and other natechs suggest new approaches to the spatial-temporal elements of infrastructure risk.

14.4 Digital Ethnography and Data by Default

The most notable responses to the flash floods in Colorado and Hurricane Isaac as it moved through the petrochemical corridor of Cancer Alley occurred beyond established law. Each involved an information asymmetry that was leveraged to achieve otherwise elusive goals. Each sought to bring to the fore the complex systems that are subject to natural hazard triggers with increasing frequency. Those triggers leave behind an inventory of "best case" impacts that can serve as proxies for cumulative, delayed, distributed, and nonlinear impacts that our statutes find difficult to address.

The first response leverages community data via new spatial media, most notably participatory geographic information systems (PGIS) (Connors et al. 2012). During each of the above natechs, the public augmented and even surpassed the state's ability to characterize infrastructure releases and their impacts. The origins of PGIS include military and intelligence technologies repurposed for commercial use, such as GPS satellites, digital mapping, and simplified geographic information systems for desktop and handheld (via smartphone) use (Kurgan 2013). Microblogs such as Twitter, application programming interfaces that allow users to geotag their microblog posts, commercially available dynamic GIS content, and other tools enable PGIS. These elements give citizens new ways to collect, represent, visualize, and validate locational data. PGIS has seen recent application in UOG fields. Projects piece together everything from the precise route of the Keystone XL pipeline (from disparate crowdsourced and public source material such as mile post markers and water crossings) to the location of active wells and waste pits (through scans of aerial and satellite imagery), which can then be used as distance-specific variables for epidemiological research (Bachand 2014; SkyTruth 2014a).

PGIS featured in the response to Hurricane Isaac and the Front Range floods. At the center of this work along the Gulf Coast was SkyTruth, a nonprofit based in West Virginia that uses "satellite and aerial images, digital mapping, data analysis, and digital graphics to investigate and illustrate environmental issues" (SkyTruth 2014b). One of the services provided on its web site is the "SkyTruth Alert." The source material for an alert consists of incident reports to the National Response Center, which are augmented with further data and analysis, including latitude/longitude, spill sheen size, volume, and minimum estimates of hazardous materials released (SkyTruth 2014c). The alerts range from discrete accidents, such as a six by six mile slick near an oil platform in the Gulf of Mexico, to slow-motion crises such as one that involved a Taylor Energy rig destroyed by Hurricane Ivan. The rig commanded 28 oil and gas wells south of the Mississippi in the Gulf. Now its mangled remains sit hundreds of feet below the surface. After efforts to plug the wells were abandoned, an international well control company created a proprietary plan to manage the oil flow. SkyTruth alerts characterized the chronic spill using NOAA satellite data, showing slicks that extended miles from the site. Another active purveyor of PGIS is FracTracker. Founded at the University of Pittsburgh in June 2010, FracTracker's mission is to explore the spatial elements of shale drilling (FracTracker 2013a, b). It encourages experimental map creation by the public (2400 active users in its first 2 years of operation) through the creation of projects that focus on the locational aspects of UOG—access roads, freshwater sources, geologic strata, and equipment use, among others. The projects work as follows: FracTracker maintains a data repository, where users upload datasets (over 400 so far) using an import wizard. A web site offers training workshops and encourages "peer review" of the data. A mapping interface lets users link the data sets in novel combination to create "snapshots" that can either be locked and auto updated or further tweaked (Michanowicz et al. 2012).

During natechs, PGIS platforms foreground the elements of environmental right-to-know that are otherwise ignored. They collapse data from required "immediate" reporting and "annual" inventories to encourage a mid-range (near-term) situational awareness. They do so in emergent spaces, irrespective of facility boundary or artificial reporting district such as air quality control regions—the internal, multi-site, domino, and disparate impacts of a common air basin, watershed, or substrate. During Hurricane Isaac, Skytruth partnered with several groups to operate at these scales (Louisiana Bucket Brigade 2012; Louisiana Environmental Action Network 2012). They detailed oil and gas infrastructure in the projected path of the storm, created a map of citizen-reported chemical releases, and augmented National Response Center reports with layers of data from earth observation satellites, aerial surveys, National Oceanic and Atmospheric Administration data, and flyovers to collect pre-storm facility conditions and post-storm sheen and anomalies. They used the data to construct more accurate release estimates and root-cause analysis. The Front Range floods were another example of regionally dense and dispersed infrastructure that was not immediately accessible to inspectors or even operators. In these circumstances, PGIS can be used to identify, tag, geolocate, and present sheen, overturned or ruptured tanks, and breached berms, among other equipment (SkyTruth 2013). For example, one FracTracker project relied on USGS streamflow gage station and National Wetlands Inventory datasets as a base, overlaid with mapped shale plays. The project offered real-time stream discharge and height data, including for areas in the flood impact zone (FracTracker Alliance 2013a, b).

The advantage of PGIS over state-sponsored data begins with its ability to leverage local knowledge, by subjecting it to peer review within a user community, validating its claims, and rendering it multi-site. Combined with historic spatial data and augmented emergency notices, PGIS can reveal patterns and relationships that are otherwise obscured by aggregate facility, county or other data units. Qualitative data and field reporting (based on lived experience and observation as citizens go about their daily routines) is otherwise confined to a single case or sacrificed in standard-form disclosures. Through PGIS, it is compiled and linked across vast distances, revealing system effects (Sylie and Albright 2014). These digital ethnographies overcome the primary barriers to UOG research, which are noted under even normal conditions. They include variance (e.g., acute and subchronic health symptoms, topographic features, weather patterns such as inversions, equipment amalgams), thresholds (e.g., impacts by family or individual that do not trigger formal complaints or notices of violation), clusters (e.g., intensity of development by well pad or field), and stages (e.g., irregular life cycle applications) that heighten cost and increase confounding factors for public health research (Moore et al. 2014; Colborn et al. 2013; McKenzie et al. 2012). In so doing, PGIS can identify, reconstruct, or track cumulative impacts that would otherwise be lost to discrete scales and regularized reporting.

While the community impacts targeted by PGIS are discontinuous and dispersed, most are not the product of black swan events. The few natech inventories available suggest sequences that, while complex in the aggregate, are amenable to standard risk assessment when viewed in isolation (Antonioni et al. 2009). A rain event leads to pump failure, containment breach, overflow, and hazardous materials washed into storm water. A certain hurricane wind speed leads to shutdown and startup procedures, a failed flare stack, and an air release. These examples include a natural event that results in one or more damaged equipment categories (storage, process, auxiliary), damage modes for each equipment category, chemical releases, and final scenarios (dispersion, explosion, reaction of water and released chemical)

(Cozzani et al. 2010). Changes to specific equipment and facility functions, and their ability to remain in or return to a safe state, reveal a second natech asymmetry: industry hazard data. For example, UOG infrastructure operators have extraordinary sensory power—seismic imaging, satellite networks, supercomputing hubs, and other assets scattered around the world. While PGIS can leverage local knowledge to improve emergency notification and response, it is rarely used to encourage hazard mitigation. For that, we need to leverage industry knowledge.

The Front Range floods are a notable example. During the floods, COGCC lacked access to several categories of equipment failure as they occurred, given high-water conditions and limited inspection personnel. Industry, on the other hand, was able to monitor wells from air and ship, and from pressure sensors located inside wells. Owners and operators constructed rapid inventories of wells and production equipment near waterways, immediately before floods converged on the impact zone. They sent remote signals to shut in most wells. State inventories, including those gathered under EPCRA-styled state laws, lacked the precision of industry data (e.g., wells located near drainage areas, precise mix of chemicals stored on well pads immediately pre-flood) (Colorado Oil and Gas Conservation Commission 2014). By some accounts, nearly all of the data on pre-flood storage and post-flood spills and releases in the impact zone were provided by industry (Interview with former Environmental Protection Agency official 2014). A COGCC staff report gave examples of resources (such as storage pits), "potentially in jeopardy due to a flooding event," whose precise locations were unknown to state inspectors and first responders. Even "updated physical maps showing the location and identification of local oil and gas facilities" were not available to emergency personnel. Chemical data required under state laws were sometimes posted on facility signage that proved "within a zone of danger" during the natural hazard. At one site, "vapors released by a damaged oil and gas facility kept first responders so far back they were unable to determine important information quickly" (Colorado Oil and Gas Conservation Commission 2014).

The gap between usable industry and state data for hazard mitigation is striking. But Colorado is not unique in its inability to mitigate the unique elements of natechs. Those include multiple and even cascading equipment failures, releases that defy immediate, facility-specific reporting, and a struggle to gain situational awareness at a scale where common mode failures, previously unknown interdependencies, and other patterns emerge. Few laws, in the United States or elsewhere, address natech risk (Steinberg et al. 2008). Natural hazards are normally absent from process safety analysis and risk management plans. Chemical accident prevention does not require certain risk reductions unique to natechs such as domino or cascading events. Reporting and other disclosure laws fail to capture the primary characteristics of equipment failure and natech chemical releases. Even targeted programs at the state level, such as CalARP response planning for chemical releases due to seismic activity, do not have to address simultaneous releases (CalARP Program Seismic Guidance Committee 2014). Yet existing authorities could be used to leverage hazard data that, for now, are uniquely available to owners and operators.

One approach would be to add a "penalty default" to existing reporting, process safety management, and risk management plan requirements (Coglianese et al. 2004). Even the limited natech inventories available show specific damage modes and final scenarios that are the result of natural hazards. That information would be used to require, in areas vulnerable to specific disaster types, a simplified, mostly qualitative risk assessment. A penalty default is a harsh provision that kicks in unless a regulated party shows that a less stringent requirement would be appropriate. The most storied example in environmental law is NEPA's environmental impact statement requirement, which a party can avoid by showing that projected impacts are not "significant (Karkkainen 2003)." In the case of natech risk, firms would engage in screening-level risk assessment for all similar equipment and functions employed by an owner/operator in a vulnerable area (watershed, flood impact zone, coastal region). The methodology would focus on a small number of consequences, such as toxic dispersion, reactions, and explosions. The scope of off-site consequences would be modeled after Japan's Prevention of Disasters in Petroleum Industrial Complexes (PDPC) law. Under the PDPC, facility sites in a natech-prone territory (e.g., seismic zone) are considered part of the same "industrial complex" for purposes of planning and mitigation (Krausmann and Cruz 2013). Thus each party would have to assess its natech risks in light of infrastructure breaches, domino, and other non-facility-specific events in the vulnerable area—beyond its facility or installation boundary.

The provisions would encourage owners and operators to avoid more expensive "penalties," such as quantitative risk assessment or additional process safety requirements. The latter may soon be added to the baseline requirements for oil and gas infrastructure, as OSHA considers changes to PSM standards that presently exempt the industry (Kaelin 2014). These standards could be part of the penalty default for UOG equipment in floodplains. Penalties would be avoided when screening-level analysis, supplemented by voluntary mitigation (e.g., repositioned storage, source reduction, increased tank capacity, secondary containment), holds categories of risk to within threshold limits. Thus, the penalty default would operate like a mitigated "Finding of No Significant Impact" under NEPA. The threshold levels would be revisited and adjusted over time, as a growing number of natural hazard triggers continue to stress a category of infrastructure. This dynamic would leverage closely held industry data to encourage *ex ante* hazard mitigation and emergency preparedness. A secondary, but no less important result would be to increase *ex post* knowledge of infrastructure risk, as the data are collected, made available through central repositories, and used to adjust penalty thresholds.

14.5 Natech as Proxy

The intersection of natural hazards and chemical infrastructure reveals limits to our right-to-know laws. Beyond the exemptions, thresholds, listing failures, and data sharing shortfalls that plague the regulatory commons, the framework must be stretched to account for unique temporal and spatial elements of natech risk. PGIS and hazard mitigation by penalty default can foreground some of those risks. The temporal risks include ongoing, simultaneous, discontinuous, and cascading chemical releases. The spatial risks include breaches of infrastructure that are isolated, inaccessible, and dispersed. PGIS addresses these risks by improving situational awareness through distributed local knowledge and data augmentation, the scale of which can adjust to match the shifting boundaries of an ongoing hazard. Penalty defaults, by contrast, encourage ground-up inventories of release scenarios that are unique to a vulnerable region, with threshold reporting requirements ratcheted up or down as knowledge of infrastructure risks increases. By better aligning right-to-know with natech risks, we advance a related and heretofore elusive goal in environmental protection. We encourage disclosure, assessment, and public discourse about the levels of systemic risk that we are willing to accept.

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Part V
Risk Management: Decision Frameworks

Chapter 15

Private Versus Public Insurance for Natural Hazards: Individual Behavior's Role in Loss Mitigation

Peter Molk

Abstract This chapter explores how insurance markets can be used to manage social exposure to catastrophic risks. Insurers set premiums to reflect underlying risk levels that they calculate using their best actuarial science. This process gives individuals private incentives prospectively to mitigate risks of loss. Private insurers, however, frequently exclude natural hazard losses from coverage, removing the private loss mitigation incentives from the market and leaving individuals without insurance against natural hazards, unless government-provided or – sponsored plans step in. These government programs amount to a species of public insurance against natural hazards. The chapter explores problems inherent in these public programs and finds that private insurance provides a viable alternative. Conventional explanations say that private insurers exclude natural disaster losses, and indeed are incapable of covering these risks, because of the difficulty in insuring highly correlated, high-dollar losses. However, I show as a matter of both theory and practice that these explanations do not fully explain private insurers' behavior. Instead, I argue that insurers exclude natural disaster losses because of costly market contracting between insurers and policyholders. Information imbalances between policyholders and insurers and coordination failures among insurers lead to an equilibrium where natural hazard coverage is sacrificed for lower premiums. This analysis suggests that a regulatory response focusing on mitigating or compensating for contracting costs could reinvigorate private insurance's role in managing risk and offer significant benefits. Throughout the chapter I draw from the United States flood insurance program, a 50-year project run by the federal government that has experienced representative degrees of successes and failures, to show the practical implications from this analysis.

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15.1 Introduction

Natural disasters routinely inflict tremendous social losses, both of life and of property. Catastrophe-related losses exceeded $100 billion in 2013, a relatively quiet year compared to the $400 billion in losses of 2011 (Munich Re 2014). Various techniques are employed to reduce these losses. One, refined by many of the chapters in this volume, is to focus on structural engineering measures, such as building codes or public works programs. Another strategy is to encourage individuals to take prophylactic action that mitigates potential losses from natural hazards, such as by storm-proofing structures or siting in safer zones.

This chapter explores the potential role of insurance in achieving this latter goal of encouraging individual mitigation behavior to reduce losses from natural hazards. In particular, it contrasts two ways of insuring against loss: private insurance and public insurance. Ultimately, it argues that private insurance offers important but neglected advantages for insuring against losses from natural hazards that may not be attainable through public insurance programs.

The chapter begins by showing how insurance encourages private actors to mitigate disaster losses voluntarily. Insurance premiums are powerful signals that encourage policyholders to undertake socially efficient investments in loss prevention. In revealing insurance's loss-prevention potential, I contrast the strengths and weaknesses of private and public approaches. Ultimately, while public insurance offers theoretical advantages over private insurance, public insurance can leave much to be desired in practice.

This chapter's second goal is to make the case for why private insurance is more viable than traditionally assumed. Typical theories assume that the highly correlated high-loss nature of natural hazards make them uninsurable by private companies, which explains why private insurers refuse to cover these losses. I show how, as a matter of economic theory, this assumption is mistaken. The chapter offers an alternative explanation for private insurers' behavior that focuses on costly marketplace interactions between insurers and consumers. Information imbalances between consumers and insurers and coordination failures among insurers produce an equilibrium where natural hazard coverage is eliminated in favor of lower premiums. The implication of this explanation is that a careful regulatory approach could harness the loss-mitigation benefits that private insurance promises in the context of natural hazards. These benefits would be particularly valuable in contexts where public insurance's theoretical benefits have been unattainable. Throughout the chapter, I use the case of the United States' flood insurance market as a representative example of the tradeoffs between public and private insurance.

15.2 How Insurance Reduces Risk

Insurance companies set premiums to reflect the insurance company's expected payouts over the life of the insurance policy. These expected payouts are largely determined by two components: the probability and the severity of potential losses, and the severity of that loss. This relationship can be expressed as a simplified formula:

$$\text{Premium}(t) = \int_0^P x f_x(x)dx + \alpha(t) + \rho(t) \tag{15.1}$$

where P = insurance policy's limit of liability; $f_x(x)$ = probability density function for financial loss, x; $\alpha(t)$ = insurer's fixed costs incurred in year t for the policy; and $\rho(t)$ = build-up or draw-down of insurance reserves.

Reductions in the likelihood of positive financial losses, especially severe losses, reduce the overall expected losses during the policy period. Consequently, since the insurance premium is based on overall expected losses, a reduction in the likelihood of positive financial losses reduces the insurance premium.

This relationship among loss probability, loss magnitude, and insurance premiums gives policyholders the financial incentive to undertake efficient loss mitigation measures. As long as the resultant discounted reduction in premiums exceeds the cost of reducing either the probability or the expected magnitude of a loss, it makes financial sense for the policyholder to undertake mitigation. These steps could range from relatively easy measures like installing wind-resistant shutters and roofing, to more intensive measures such as raising one's house above the 100 year floodplain, to more proactive approaches like locating a new house outside an earthquake zone. Each of these steps reduces the expected losses from future natural disasters, making them desirable from both an individual and a social perspective.

Of course, even without insurance, individuals should undertake efficient disaster mitigation that saves them more in discounted expected value than it costs. In many ways, however, insurance companies are superior at providing the appropriate loss mitigation signals because individuals have difficulty in internalizing natural disaster costs and benefits. An insurer-provided premium reduction gives consumers a digestible dollar amount with which it is relatively easy to determine if the mitigation measure makes financial sense. Left to themselves, individuals would have to estimate both the reduction in loss probability and in loss magnitude from a particular mitigation procedure, in many ways an impossible task for individuals to accomplish. Insurance companies, which do these calculations every day, can do this with comparative ease and provide the conclusion via premium differentials.

Unfortunately, these valuable price signals are not sent for natural disaster risk reduction because although insurance companies covered natural disasters in the past, today insurance companies exclude losses from natural disasters (Manes

1938). Standard homeowners insurance policies, for example, exclude losses from earth movement, flood, and, for Gulf Coast states, wind. Commercial property and business policies typically exclude earth movement, flood, and wind. Neither homeowners nor auto insurance covers losses from nuclear disasters or war. Private market endorsements that add coverage for these events can sometimes be found for commercial property at additional expense, but often endorsements are unavailable in the residential consumer market, and when available must be individually added on rather than coming standard. When insurance premiums do not cover losses from natural disasters, the relevant price signals are not sent, which decreases the mitigation undertaken by individuals and increases society's exposure to future natural disaster losses.

The most popular theory for why private insurance companies choose not to cover natural disaster losses is that losses from these events are too large and too highly correlated for insurers to bear them (Abraham 2010; Avraham 2012; Jerry and Richmond 2012). When losses are highly correlated, insurers' claims experience is expected to be lumpy—the presence of one claim implies a likelihood of many claims. Several years may result in no claims, but some years will have gigantic levels of claims, and the strain of being prepared for a disaster year means insurers must either charge high premiums, or face the risk of bankruptcy. The conventional wisdom is that insurers choose to exclude these risks from coverage, rather than expose themselves to the year-to-year uncertainty endemic to correlated risks. Contrast this with uncorrelated claims, which present a steady level over the years and are comparatively easy for insurance companies to cover.

Regardless of whether the conventional explanation is accurate, it is a fact that private insurers exclude natural disaster losses. To fill these gaps, governments step in with government-supported insurance. This intervention generally follows one of two approaches: either the government directly provides insurance, as with flood insurance in the United States and the Netherlands, or the government subsidizes insurance industry losses above a predetermined threshold, as with the United States' terrorism insurance program and flood insurance in France and the United Kingdom (Faure and Hartlief 2006; Van den Bergh 2006).

At least in theory, public insurance can prove extremely effective because a government-backed product offers several advantages over private insurance (Arrow 1978; Kunreuther 1996). A government is unparalleled at being able to aggregate and diversify risks. Like private insurers, a government can diversify widely across a variety of risks, but unlike private insurers, it can use its powers of compulsion to bring more risks into the pool, which maximizes risk spreading, in turn maximizing consumer participation in the insurance market and minimizing adverse selection worries—where low-risk individuals drop out and risk an unraveling of the insurance market. Additionally, unlike private insurers that face a bankruptcy constraint, a government can diversify across time to deal with lumpy claims, paying back current deficits with future earnings. Finally, governments have a taxing power that could also be employed to cover lumpy claims. Private insurers have no such analogue.

Despite these advantages, the practice of public insurance often fails to achieve its theoretical pinnacle (Priest 1996, 2003). All too often, premiums become divorced from underlying risk levels. The case of United States flood insurance is illustrative. In the midst of rapid coastal development, public flood insurance does not vary the premium for many properties according to the risk of loss, such that in extreme cases, the premiums charged represent only 10–30 % of the expected losses in any given year (FEMA 2013). Although Congress attempted to reform the program and tether flood insurance rates to the actuarial risk as part of the Biggert-Waters Act of 2012, the reforms were retroactively rolled back in 2014 due to public and political pressure. The United Kingdom and France exhibit similar separation between risk level and premiums (Huber and Amodu 2006; Van den Bergh 2006).

Political economy dynamics suggest that the break between risk level and premiums exhibited with flood insurance is not unusual. As those familiar with interest group theory know, small groups bearing comparatively large losses are disproportionately more likely to influence decision-makers than are large groups with diffuse benefits. Government-sponsored insurance fits this model well. Natural disaster losses concentrate disproportionately among a relatively small and risky part of the insured population. Flood damage, for instance, is disproportionately more likely to occur with risky coastal properties than inland ones. Charging rates that reflect properties' true expected losses concentrates large price increases among a relatively small group—approximately 20 % of those in the United States with flood insurance (Fugate 2013)—while producing comparatively smaller price decreases among the more diffuse general population. As a consequence, the clamor to prevent actuarially-fair rates is significantly louder than the calls to impose them, even though 80 % of those with flood insurance would benefit from fair rates. The story is repeated across many public insurance regimes. The problem with this outcome is that the resultant premiums send the wrong signals for disaster mitigation. Instead of encouraging preventative measures, actuarially-unfair rates encourage development in natural disaster-prone areas and deter efficient risk mitigation, perversely increasing the costliness of future disasters.

Alternative programs where a government leaves premium pricing and underwriting to private insurers and assumes a portion of losses above a threshold, instead of directly writing public insurance, offer an important advantage. Unlike governments, private insurers face less pressure from concentrated groups, and competitive forces push them to charge premiums that accurately reflect the level of underlying risk. Yet this situation, too, is imperfect. Subsidies from the government backstop get passed along, at least in part, to policyholders via reduced premiums, and if premiums drop below the rate that reflects the expected value of a loss, then we are left with the same problem of perversely encouraging development in high-risk zones and deterring efficient mitigation. This again contributes to increasing losses in future natural disasters.

One way to avoid these challenges is for private insurers to be wholly responsible for covering natural disaster losses. In Sect. 15.3, I challenge the conventional wisdom about private insurers' inability to handle correlated natural disaster losses.

I then make recommendations for how better to integrate private insurers into disaster risk management and reflect upon the promise of this strategy for reducing the total losses caused by natural hazards.

15.3 The Case for Private Insurers

Recall that conventional accounts say that private insurers refuse to cover losses from natural disasters because the losses are too difficult to insure—their correlated nature necessitates high premiums or facing bankruptcy risk. Yet while it is undoubtedly true that correlated risks are more difficult for insurers to cover than uncorrelated ones, the relevant question to ask is not whether, in absolute terms, correlated risks are difficult for insurers, but rather whether insurers are in a worse position to bear natural disaster risks than are individuals or the government, because the risks must be borne by some entity. By “worse,” I mean that under normal market conditions, individuals or governments would prefer to cover the risks of financial losses from natural disasters rather than pay insurance companies a mutually beneficial price to assume them. I have already pointed to problems inherent with having governments bear these risks. There are also several reasons to believe that individuals are likewise at a comparative disadvantage in bearing these risks.

Most prominently, individuals are unable to diversify away natural hazard risk in any meaningful sense. Most individuals own at most one home so that if disaster hits, their personal and real property will be entirely wiped out. While consumer bankruptcy offers them a fresh start, individuals who face a probability of having the bulk of their wealth eliminated would be willing to pay a sizable fee, above and beyond the expected loss amount, to avoid it. This is particularly true when individuals are risk averse, as they are in a variety of loss-avoiding circumstances. The question then becomes whether the extra amount that individuals would pay to avoid risk would more than compensate insurers for taking on the risks associated with covering correlated losses.

There are several reasons to think it would. First, the additional risk premiums that individuals are willing to pay can be staggering. Popular products like flight or disease-specific life insurance imply extremely high-risk aversion or irrationality by insurance purchasers that can lead to premiums far exceeding expected losses (Eisner and Strotz 1961; Johnson et al. 1993). The greater the premium that individuals are willing to pay, the more likely it is that the overall premium will prove attractive enough for private insurers to take on.

Second, while natural disaster risks are correlated, insurers can still diversify these risks to a meaningful extent such that even significant natural disasters may not impose unbearable losses on the insurer when compared to its overall book of business. It is very common in modern insurance markets to see companies writing business on a country- or world-wide scale, which mitigates their exposure to any one natural disaster. Additionally, insurers commonly diversify across different insurance products, writing a mixture of property, liability, auto, and life insurance policies that have differential exposures to natural disasters. A natural disaster whose effects are concentrated on property, for example, has a lesser impact on insurers who devote only a portion of their portfolio to property risks than insurers that concentrate exclusively on property coverage.

Third, insurers have access to worldwide capital markets to further diversify risks beyond their own books of business in ways that individuals cannot replicate. It is routine practice for insurance companies to cede a portion of the risks that they underwrite to other insurance companies, allowing insurers to exchange risks among one another. Insurers can further cede risks to global reinsurers, who act as insurers for insurance companies and allow insurers to cap their financial exposure to natural hazards at a fixed ceiling. Insurers can even offload risk to individual investors around the world by using financial structures called "sidecars" or selling cat bonds or other insurance-linked securities. These techniques allow even small regional insurance companies to achieve worldwide diversification.

In addition, insurers can further limit their maximum exposure to natural disaster risks through corporate structure planning, by cabining correlated activities within separate subsidiaries. In the many countries that recognize limited liability business structures, when insurers group correlated risks within subsidiaries, correlated losses are limited to the subsidiary's assets and do not spill over into the insurer as a whole. State Farm, for example, carries out property insurance for California, Texas, and Florida in three separate subsidiaries, limiting the company's exposure to losses in any of these three areas (State Farm 2014). While this practice may weaken the value of the insurance to policyholders in those states and thus reduce premiums for insurance sold in those jurisdictions, it is an effective way of further diversifying otherwise-correlated risks at a company level.

On top of these techniques can be layered the theoretical assumption that insurers, like any large firm, behave in a risk-neutral manner. Insurers owned by investors, and to a letter extent those "mutuals" owned by policyholders, are risk neutral, having neither a preference for nor a reluctance to taking on risk (Molk 2014). When contrasted with risk-averse private individuals, insurers are in a better position to bear risks of loss even setting aside their additional comparative advantages in risk management.

In summary, even though natural disaster losses may be correlated, private insurers have several ways to "break" the correlation to achieve a diversified result that is unavailable to individuals. Indeed, in some non-property markets, insurers already employ these techniques to cover correlated risks. Life insurance contracts, for example, have few meaningful exclusions beyond limited ones for fraudulent applications and for suicide, leaving insurers open to losses from correlated risks including natural disasters, nuclear catastrophe, or war, yet insurers voluntarily cover these risks. There is reason to think they could also do so in property insurance markets. In fact, private property insurers in the United Kingdom already cover losses from natural disasters pursuant to government regulation, although regulator-imposed price constraints distort the signals that are sent to policyholders (Huber and Amodu 2006).

Thus, private insurers look better situated to bear the risks associated with natural disasters than are individuals. Doing so, of course, would provide the all-important price signals that incentivize private mitigation. If private insurance companies are in a superior position to assume these risks, though, why do they exclude these risks? In the following subpart, I develop a potential explanation.

15.3.1 Why Do Private Markets Fail?

If, as I have argued, private insurers are in a superior position to bear financial risks from natural disasters, why as a practical matter do private insurers exclude them? Surely when public insurance is unavailable, some contracts could be made where the most risk-averse individuals transfer these risks back to private insurers at a favorable price for all parties. And even when there is public insurance available, as there is with flood insurance in the United States, some private individuals may prefer dealing with private insurance companies rather than accept the public option—particularly when, as happens with some relatively safe flood insurance properties, the public insurance policy charges rates that far exceed the expected annual loss (FEMA 2013).

I provide a possible explanation that stems from the transaction costs involved in consumer insurance contracts. Coordination failures drive insurance to an equilibrium of offering uniform policies that exclude coverage while information imbalances between policyholders and insurers keep insurers from adding this coverage back in.

First, insurers coordinate on adopting uniform policy language that, in countries across the world, excludes natural disaster losses. Insurers are loathe to vary significantly the terms in their insurance contracts (Schwarcz 2011). By coordinating on common terms, insurers can benefit from each other's experience, both with claims and with litigation. In the United States, insurers base residential property insurance contracts off a standard form contract developed by the Insurance Services Office (ISO), which excludes damages associated with natural disasters. ISO then makes available to insurers the claims experience from companies using its insurance contracts, which can greatly facilitate insurers' underwriting practices as they benefit from knowing how new prices and products can be expected to perform based on other insurers' experiences with them. Significant variations from this standard contract language render the shared data less useful, which will tend to push insurers to coordinate on language. Additionally, by coordinating on tested language that has been subject to repeated judicial scrutiny, insurers gain predictability over how future litigation will proceed (Boardman 2006). This predictability can carry significant value, again deterring insurers from varying terms from the standard form.

Even if there were few benefits from uniformity, it still makes little sense for individual insurance companies to expand coverage. Policyholders are notorious for failing to read their policies, instead assuming that they are buying some general insurance "product" that will cover them in the event of a loss. This assumption means that many policyholders *already* think they are covered for natural disaster losses under a standard insurance policy (NAIC 2007). Those individuals, of course, would be unwilling to pay higher amounts for policies that cover what they think is already covered, and an insurer seeking to insure these losses would have to incur additional costs to convince these individuals about the desirability of purchasing their more-expensive coverage. And for those policyholders who recognize that losses from natural disasters were not covered in standard contracts, existing sales practices make it particularly difficult for them to get it even if insurers offered it. In the United States, policies are not made available to consumers until those consumers have already agreed to purchase the policy. This practice means that consumers cannot evaluate different insurers' coverage comprehensiveness and results in policyholders' basing their purchase decisions almost exclusively on the highly salient premium figure (Schwarcz 2011). When individuals are shopping around exclusively based on price, insurers have financial incentives to minimize those prices, rather than to add in additional coverage.

An effective way to minimize these prices is to carve out low-salience coverage that is not cheap for the insurer to cover. Most policyholders would not notice the absence of this coverage, and those that do might not be particularly troubled as long as they retain coverage for the majority of loss events. Coverage for natural disasters satisfies all these criteria. When natural disasters aren't hitting close to home, policyholders do not worry about the missing coverage. By the nature of competition solely along price, once one insurer agrees to cut this coverage, others will be pushed to follow suit. What arises is the current market where coverage for losses from natural disasters is not available in standard contracts so that even those who might want coverage for natural disasters do not receive it by default.

Of course, even though standard contracts exclude natural disaster losses, insurers could cover them through add-on endorsements available for additional purchase by the few policyholders who desire it. Using endorsements in this way allows insurers to tailor their products to appeal to different market segments, cutting costs for most policyholders but offering the superior—and more expensive—policy for those who want it. Yet while this is the routine practice in commercial property insurance, natural disaster endorsements remain generally unavailable in private consumer markets. One possible explanation for this dichotomy is that offering these endorsements in the consumer sphere may carry little reward yet incur substantial risk for insurers. Potential rewards are small, because individual consumer contracts carry comparatively small premiums relative to their commercial counterparts so that providing individualized additions may not result in much additional revenue. Even more importantly, insurers who advertise and make available endorsements may turn away many other consumers who did not even care about the additional coverage. Consumers generally find only a few terms of a contract to be salient (Korobkin 2003), and the insurer that draws attention to its natural disaster exclusions by selling an add-on may inadvertently increase the exclusions' salience and deter consumers who had not otherwise thought to look for natural disaster exclusions. For these consumers, even a competitor with *no* signals—an insurer with no endorsements—is better than one sending negative signals about its default product through making endorsements available. This concern may be lower in commercial markets, where consumers are thought to be more sophisticated, and could explain endorsements' use there. While insurers could spend to educate non-commercial consumers about the importance of obtaining coverage for natural hazards and solve the signaling problem, these expenditures are quintessential public goods that result in competitive advantages accruing to competitors. Therefore, the spending does not take place.

Taken together, what we have is a situation akin to a coordination failure among insurers. No single insurer has the incentive to add in natural disaster coverage for standard contracts when competitors do not likewise offer it. Quite the contrary: individual insurers have the incentive continually to underprice their competitors, and an effective way to reduce price is likewise to reduce coverage via exclusions within the limits allowed by regulators. While all parties may be better off if insurers uniformly offered comprehensive insurance—insurers because they charge higher premiums and earn more profits, and policyholders because they receive comprehensive coverage for the underlying loss they want covered—this outcome will not occur with unregulated markets (Stempel 2013).

15.4 Possible Regulatory Responses

If left to their own devices private insurers will not cover natural disaster losses, what is to be done? One solution would be to let the losses fall where they may, leaving private individuals to suffer them. Yet because individuals are in such a poor position to bear backbreaking losses, this outcome is not particularly desirable. Nor is it often practically feasible when governments feel compelled to step in and mitigate losses after disasters.

Governments could alternatively intervene to provide the insurance, but as has already been discussed, the practical implementation of these programs often leaves much to be desired. Despite their superior position at bearing risk, public insurance programs routinely result in underpricing high levels of risk, which promotes risky behavior that leads to greater losses of valuable assets and valuable lives with future natural disasters.

An ultimate solution may be covering these risks with private insurers. If failures in private insurance markets give insurers the incentive not to cover these risks, solving the coordination and information problems may take a regulatory response that mandates insurers who choose to write a particular type of insurance to cover various natural disaster risks. This type of mandate should certainly not be undertaken lightly, as in past cases it has led to insurers' fleeing those jurisdictions and an unraveling of insurance markets (Hayden 1904). However, it has met with success in the United Kingdom, where private property insurers are required to cover losses from natural disasters (Huber and Amodu 2006).

There are ways to alleviate transitional insurer concerns with such a regulatory response. In markets that would move from public insurance to private provision, governments can share their underwriting experience with new insurers to facilitate their immediate operations, rather than leaving private insurers to muddle through the early years until a reliable record of past results can be built up. In the case of United States flood insurance specifically, private insurers have noted that access to historical data from the federal flood insurance program could enable them to better assess risk and enter new markets (GAO 2014).

Government regulators could also be sure not to unduly interfere with private insurers' actuarially-fair pricing. Insuring natural disaster risks may require substantial premium hikes to cover insurers' increased exposure. If regulators refuse to allow insurers to enact these increases, not only will premiums' incentive effects on disaster mitigation be undermined, but also the likelihood that insurers will completely pull out of a market increases. There are instead other nondistortionary ways that regulators could address the fairness or equity concerns that rising insurance premiums present. For instance, governments can provide citizens with vouchers to be used for purchasing insurance, and as long as the voucher amount does not vary with the level of underlying risk—meaning that vouchers cannot be more generous for those facing the most sizable premium increases—then premiums' mitigation incentives can be mostly preserved while keeping insurance relatively affordable. Or governments could cover legacy risks that built homes or otherwise relied on subsidized rates in making decisions that are difficult to reverse while allowing private insurers to charge new risks their actuarially fair rates.

Finally, for risks that have never been covered systematically by either private insurers or public insurance, a phased government support program may be the most appropriate. For example, after the terrorist attacks of September 11, the United States federal government required that all property insurers make available terrorism coverage for commercial properties. Yet recognizing private insurers' reluctance to do so without any meaningful underwriting history or predictive model, the United States government provided for a federally-funded backstop that assumed the risks of any losses above a predetermined threshold, thereby capping private insurers' maximum exposure. As discussed earlier, this type of cap reduces to some degree premiums' loss mitigation incentives, but it very effectively promotes the initial entry of private insurers. Once several years pass and private insurers gain underwriting experience and develop models, this type of government support can then be removed. Such was the original aim of the United States terrorism coverage program, although the fact that it has been extended three times for a total of fifteen years past its original 2005 horizon shows the practical difficulties in committing to a "temporary" subsidy.

Of course, just because one approach is tried does not mean regulators must remain blindly wedded to it. In fact, there is great value in reassessing programs' success, revising them as appropriate, and, to the extent possible, designing regulations to promote flexibility (Molk and Rowell 2016). With that said, a temporary government backstop may be particularly important in avoiding long-term disruptions if insurers would otherwise balk at new requirements and entirely withdraw from insurance markets.

15.5 Conclusions

Innovation and experimentation by private insurance companies could help spur advancements in methods to address not just the natural disasters that are a problem today, but also the anticipated problems on the horizon. Global warming, for example, is expected to cause widespread property damage through rising sea levels and new weather patterns (Wuebbles 2015). Insurance companies that cover these damages will provide innovative solutions for mitigating resultant losses, just as insurers today do for a variety of property, automotive, life, and health related costs.

Private insurers are in a far superior position to bear risks of loss from natural disasters than are individuals, and their superiority grows with the development of each new financial product and new modeling system. Traditional explanations that focus on the correlated nature of these risks to explain why insurers nevertheless do not cover them miss the fact that even though insuring these risks may be comparatively expensive, risk neutral insurance companies are still in a better position to do so than are risk averse individuals. Additionally, a system built upon private insurers may be superior in practice to a public, government-sponsored approach. Inducing insurers to overcome their reluctance to cover these risks, however, will require regulatory intervention. But in an era of multi-billion-dollar losses, it is essential to experiment with the power of private insurers and incentives, looking to the comparative successes and failures of other markets and countries for guidance. Of course, private insurance should not be the exclusive approach for loss mitigation. Government action is still important for addressing public good mitigation with public works or solving information imbalances with minimum standard building codes, where private mitigation incentives are incomplete. However, a measured approach that employs the power of private insurers behind any effort to address natural disaster risk management could prove extremely effective.

Natural disaster exposure is a significant problem. Insurance is a valuable and useful tool for reducing future losses, and it should be a part of every discussion for addressing them.

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Chapter 16
Risk-Informed Decision Framework for Built Environment: The Incorporation of Epistemic Uncertainty

Eun Jeong Cha and Yan Wang

Abstract Managing a risk to a built environment from natural and man-made hazards is an important issue for the prosperity of a nation. Risk assessment forms the basis for the risk management, which often involves uncertainties that arise from our ignorance about the risk, such as lack of data, errors in collected data, and assumptions made in the modeling and analysis. This uncertainty that arises from imprecise information is referred to as epistemic uncertainty, as opposed to the aleatory uncertainty that arises from the variability of possible outcomes. If epistemic uncertainty prevails, assessing and managing a risk rely on risk perception of a decision maker. Studies have suggested that the risk of low-probability high-consequence events tends to be overestimated by the public. Thus, the role of risk perception in risk management of civil infrastructure exposed to natural and man-made hazards becomes significant because of the potential catastrophic consequences of such risks (e.g. casualties, functional and economic losses of the built environment, etc.) to the public. The consideration of epistemic uncertainty and risk perception in risk assessment of a built environment may lead to a risk management solution that is different from what is obtained when it is not incorporated. In this study, we present a risk-informed decision-making framework that can assist decision makers, including governmental agencies that allocate limited resources to enhance the safety and security of the civil infrastructure. In this framework, epistemic uncertainty is incorporated by utilizing generalized interval probability theory and cumulative prospect theory. The framework is illustrated with an example of regional hurricane risk management for residential buildings located in Miami-Dade County, Florida, considering the effect of changing climate.

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16.1 Introduction

Structures and civil infrastructure might be subjected to various natural and man-made hazards throughout their lifetime. Assessing risks of complete or partial failure of a structure or civil infrastructure caused by such hazards forms a basis for managing those risks, which is an important issue for the prosperity of a nation. Risk assessment of such built environment often involves uncertainties that arise from our ignorance of a risk, such as lack of data, errors in collected data, and assumptions made in the modeling and analysis. This uncertainty that arises from imprecise information is referred to as epistemic uncertainty, which is distinguished from the aleatory uncertainty that arises from the variability of possible outcomes. Epistemic uncertainty exists in the assessment of a hazard occurrence in relation to its magnitude, the associated likelihoods, and the response of a structure. This uncertainty can be modeled with various mathematical formalisms, including sensitivity analysis, Bayesian approach, Dempster-Shafer theory of evidence, and theory of possibility (Dempster 1967; Dubois and Prade 1988; Shafer 1990). The consideration of epistemic uncertainty in risk assessment of a built environment may lead to a risk management solution that is different from what is obtained when it is not incorporated.

Risk assessment and management of a built environment against natural and man-made hazards require the proper treatment of risk perception from the public because of the potential catastrophic consequences (e.g. casualties, functional and economic losses of the built environment, etc.). Studies have suggested that the risk of low-probability high-consequence events tends to be overestimated by the public (Tversky and Kahneman 1992), which often influences regulatory and professional decisions in which political attitudes and policy play a role. This tendency of overestimating a risk (or sometimes underestimating a risk) has been noted and implemented in some decision models such as cumulative prospect theory and utility theory (von Neumann and Morgenstern 1953; Tversky and Kahneman 1992). However, the effort to account for the risk perception of the public for the built environment is still at its early stage (Slovic et al. 1980). In addition to risk aversion, it has been demonstrated that people also tend to have the attitude of ambiguity aversion in decision-making (Ellsberg 1961; Camerer and Weber 1992). Different from risk, which represents the situation that the information on probabilities and consequences is available, ambiguity refers to the situation that the probabilistic information is incomplete or imprecise (Camerer and Weber 1992). This uncertainty about the imprecise probability assessment is also called as metadoxastic uncertainty (Hansson 2006; Murphy et al. 2011). The lack of data and knowledge could bolster or undermine decision maker's confidence. For the majority of people, the risky prospect is perceived as more justifiable than the ambiguous one because missing probabilistic information is even worse (Keren and Gerritsen 1999). People also tend to prefer imprecise ambiguity over conflicting ambiguity, where information is inconsistent (Cabantous et al. 2011).

In this chapter, we propose a risk-informed decision-making framework that incorporates the attitudes of both ambiguity and risk. Conflicting information or beliefs are represented as interval probabilities and used to generate capacities in the cumulative prospect theory for decision-making. The framework can be used to assist decision makers, including governmental agencies, to allocate limited resources for enhancing the safety and security of infrastructure especially in the presence of such conflicting information or beliefs in the risk assessment. The framework is demonstrated with the risk assessment of a built environment under climate change.

In the remainder of the chapter, risk-informed decision-making methods that account for risk and ambiguity aversion of a decision maker are introduced in Sect. 16.2.1. The imprecise probability to incorporate epistemic uncertainties is also introduced. The proposed risk assessment framework that accommodates the imprecision of probability estimation is described in Sect. 16.2.2. A case study of hurricane risk mitigation is given in Sect. 16.3, where a life cycle cost analysis and risk management framework for built environment is provided. The impact of ambiguity and risk attitudes in risk mitigation decisions will be illustrated with the alternative mitigation strategies of housing in Miami-Dade County, Florida against the increased risk of hurricanes due to climate change.

16.2 Decision Making Under Risk and Ambiguity

16.2.1 Ambiguity and Imprecise Probabilities

In the situation of ambiguity and lack of information, Savage's sure-thing principle is violated. The principle states that if you prefer act f to act g for each of the possible states in a state partition, then you should always prefer f to g. The sure-thing principle may fail in the situation when we are unable to construct independent arguments for all the states in isolation without complete information. Various approaches for decision making under ambiguity have been developed (Ellsberg 1961; Dubois and Prade 1988; Camerer and Weber 1992; Tversky and Kahneman 1992; Keren and Gerritsen 1999; Cabantous et al. 2011; Etner et al. 2012). Uncertainty is associated with either decision maker's preference or probability. For instance, Gilboa and Schmeidler (1989) used maxmin expected utility to incorporate a set of possible prior beliefs of the decision maker. Klibanoff et al. (2005) proposed a double expectation model with two utility functions to characterize the decision maker's ambiguity attitude and risk attitude respectively. Instead of additive probability, Choquet capacity is used to represent beliefs in Choquet expected utility (CEU) model (Gilboa 1987; Schmeidler 1989) and cumulative prospect theory (CPT) (Tversky and Kahneman 1992). Choquet capacity is a generalized measure of belief in the occurrence of an event, which can be non-additive or additive. In CEU, expected utility is calculated with the Choquet integral of utility and capacity. CPT is a generalization of CEU by introducing two different capacities, one for events of gains and the other for events of losses. Similarly, the expected utility under imprecise risk (EUIR) model (Jaffray 1989; Hendon et al. 1994; Jaffray and Philippe 1997) explicitly takes imprecise probability into account where a convex set of probabilities are applied in estimating utility.

Imprecise probability can be regarded as a compact model to represent both risk and ambiguity, where the possible values of probabilities capture the inconsistency among data or beliefs. Different representations of imprecise probabilities have been developed. For example, the Dempster-Shafer evidence theory (Schmeidler 1989) characterizes evidence with discrete probability masses associated with a power set of values, where Belief-Plausibility pairs are used to measure uncertainties. The coherent lower prevision theory (Walley 1991) models uncertainties with lower prevision (supremum acceptable buying price) and upper prevision (infimum acceptable selling price) following the notations of de Finetti's subjective probability theory. The possibility theory (Dubois and Prade 1988) represents uncertainties with Necessity-Possibility pairs. Probability bound analysis (Ferson et al. 2003) captures uncertain information with pairs of lower and upper distribution functions. F-probability (Weichselberger 2000) represents interval probability as a set of probabilities which maintain the Kolmogorov properties. Fuzzy probability (Möller and Beer 2004) considers probability distributions with fuzzy parameters. Generalized interval probability (Wang 2010) has a simplified probabilistic calculus structure by adopting generalized interval for probability bounds.

16.2.2 The Proposed Risk-Informed Decision Framework in the Presence of Ambiguity Based on Cumulative Prospect Theory

When information about risks is incomplete or imprecise, the uncertainty associated with a risk needs to be differentiated from the risk itself. Decision maker's attitudes toward risk and ambiguity also need to be represented. CPT was developed to capture such subjective attitude. In CPT, two capacities c^+ and c^- are assumed for gains and losses respectively. The capacities are utilized to compute the decision criterion that is defined as the weighted average of the utilities of all the potential consequences. For a decision δ with potential events, E_j's and their corresponding consequences in rank-order, $s_n \succ \cdots \succ s_k \sim \gamma \succ s_{k-1} \succ \cdots \succ s_1$, where γ is the reference value between gain and loss, the decision criterion is

$$U(\delta) = \sum_{i=1}^{k-1}\left[c^{-}\left(\cup_{j=1}^{i}E_j\right) - c^{-}\left(\cup_{j=1}^{i-1}E_j\right)\right]u(s_i) + \sum_{i=k+1}^{n}\left[c^{+}\left(\cup_{j=i}^{n}E_j\right) - c^{+}\left(\cup_{j=i+1}^{n}E_j\right)\right]u(s_i) \tag{16.1}$$

where u is a bounded function of consequence with $u(\gamma) = 0$, $c^{-}\left(\cup_{j=1}^{i}E_j\right)$ is a capacity (probabilistic measure) that is assigned to the union of the events from E_1 to E_i with loss, $c^{+}\left(\cup_{j=i}^{n}E_j\right)$ is a capacity that is assigned to the union of the events from E_i to E_n with gain, and $\left[c^{-}\left(\cup_{j=1}^{i}E_j\right) - c^{-}\left(\cup_{j=1}^{i-1}E_j\right)\right]$ and $\left[c^{+}\left(\cup_{j=i}^{n}E_j\right) - c^{+}\left(\cup_{j=i+1}^{n}E_j\right)\right]$ are capacities (considered as decision weights) assigned to the ith lowest consequence for loss and for gain, respectively. When $c^{+}\left(E_j\right) + c^{-}\left(E_j^C\right) = 1$, Eq. (16.1) can be simplified with only one capacity $c\left(E_j\right) = c^{+}\left(E_j\right) = 1 - c^{-}\left(E_j^C\right)$. If $c(E_j)$ is an additive probabilistic measure, Eq. (16.1) is further reduced to Savage's subjective expected utility criterion, which is typically advocated in normative decision making with the subjective interpretation of probability (Fishburn 1981; Tversky and Kahneman 1992; Luce and von Winterfeldt 1994).

Under imprecise risk, the lower and upper probabilities, denoted by $\underline{p}$ and $\overline{p}$ respectively, are capacities. The lower and upper probabilities can be obtained as follows. If the terminology of the Dempster-Shafer evidence theory is used, the relationship between the lower probability and the basic probability assignment (BPA), $m(E_i)$, is established by $\underline{p}(A) = \sum_{i:B_i\subseteq A} m(B_i)$. In other words, the lower probability of any event A is computed by a summation of the probabilities of the mutually exclusive subsets, B_i's of A. With ambiguity, the decision maker's information is typically expressed by BPA's. With the lower probability of the complementary set of A, $\underline{p}\left(A^C\right)$, the upper probability is obtained as $\overline{p}(A) = 1 - \underline{p}\left(A^C\right)$.

Let us use Ellsberg's urn example (Ellsberg 1961) to illustrate how to obtain lower and upper probabilities from BPA's. Suppose an urn contains 90 balls: 30 are red (R), and the other 60 are either black (B) or white (W). That is, $m(R) = 1/3$ and $m(B \cup W) = 2/3$. Ambiguity exists about the probabilities of drawing B and W and is expressed by BPA's. We can obtain $\underline{p}(\varnothing) = 0$, $\underline{p}(R) = m(R) = 1/3$, $\underline{p}(B) = 0$, $\underline{p}(W) = 0$, $\underline{p}(R \cup B) = m(R) = 1/3$, $\underline{p}(R \cup W) = m(R) = 1/3$, $\underline{p}(B \cup W) = m(B \cup W) = 2/3$, and $\underline{p}(R \cup B \cup W) = m(R) + m(B \cup W) = 1$. The respective upper probabilities are $\overline{p}(\varnothing) = 1 - \underline{p}(R \cup B \cup W) = 0$, $\overline{p}(R) = 1 - \underline{p}(B \cup W) = 1/3$, $\overline{p}(B) = 2/3$, $\overline{p}(W) = 2/3$, $\overline{p}(R \cup B) = 1$, $\overline{p}(R \cup W) = 1$, $\overline{p}(B \cup W) = 2/3$, and $\overline{p}(R \cup B \cup W) = 1$.

Based on Hurwicz criterion, Jaffray and Philipe (Jaffray 1989; Jaffray and Philippe 1997; Philippe 2000) proposed the relation between the capacity in CPT and the lower and upper probabilities as

$$\begin{cases} c^{+} = \alpha^{+}\underline{p} + (1-\alpha^{+})\overline{p} \\ c^{-} = \alpha^{-}\overline{p} + (1-\alpha^{-})\underline{p} \end{cases} \tag{16.2}$$

where α^{+} and α^{-} are the pessimism indices. Different from Eq. (16.2), here we propose a new combination rule that explicitly incorporates subjective prior belief. Various studies (Kahneman et al. 1982; Viscusi 1985, 1989; Liu et al. 1998) have shown that people's risk perception is affected by both prior biases and new information during the learning and belief updating process that is analogous to a Bayesian decision process. Therefore, the proposed relation between capacities and probabilities are

$$\begin{cases} c^{+} = \beta^{+}q + (1-\beta^{+})\alpha^{+}\underline{p} + (1-\beta^{+})(1-\alpha^{+})\overline{p} \\ c^{-} = \beta^{-}q + (1-\beta^{-})\alpha^{-}\overline{p} + (1-\beta^{-})(1-\alpha^{-})\underline{p} \end{cases} \tag{16.3}$$

where q is the prior belief, $\underline{p}$ and $\overline{p}$ are lower and higher probabilities respectively, $\alpha^{+}, \alpha^{-}, \beta^{+}$, and β^{-} are the attitude indices. In Eq. (16.3), $\underline{p}$ and $\overline{p}$ can be regarded as inconsistent information that is derived from other sources, such as government, experts, simulation results, etc., whereas q is decision maker's own prior belief. α^{+} and α^{-} represent the degree of pessimism or ambiguity aversion of the decision maker. Pessimism is characterized by $\alpha^{+} > 1/2$ and $\alpha^{-} > 1/2$, whereas optimism is by $\alpha^{+} < 1/2$ and $\alpha^{-} < 1/2$. The confidence indices β^{+} and β^{-} indicate the confidence that the decision maker has on his/her prior conviction of risks after being presented the extra information. When $\beta^{+} = \beta^{-} = 1$, the decision maker exhibits overconfidence. When $\beta^{+} = \beta^{-} = 0$, Eq. (16.3) degenerates to Eq. (16.2) in which the decision maker purely relies on the objective information of risks and ambiguity. Therefore, Eq. (16.3) captures the dynamics of information gathering and belief update in the process of risk assessment.

The values of α^{+}, α^{-}, β^{+}, and β^{-} can be decided as follows. First, an arbitrary gain s^{+} (i.e. $s^{+} > \gamma$) is chosen. Then α^{+} is found such that the decision maker shows indifference between the following two options: (I) to receive either γ with probability α^{+} or gain s^{+} with probability $1-\alpha^{+}$; and (II) to receive an outcome that is at least γ and at most s^{+} for sure, without further information. Similarly, α^{-} is constructed by considering a loss s^{-} (i.e. $\gamma > s^{-}$) such that the decision maker shows indifference between the following two options: (III) to receive either loss s^{-} with probability α^{-} or γ with probability $1-\alpha^{-}$; and (IV) to receive an outcome that is at least s^{-} and at most γ for sure, without further information. At the same time, β^{+} and β^{-} can be collected by the questionnaire about the confidence or precision the decision-maker has by making the choices. For instance, a scale of confidence (10, 30, 50 %, etc.) can be provided for the decision maker to choose in the questionnaire.

16.3 Case Study: Retrofit of Residential Buildings in Miami-Dade County Against Hurricanes in Changing Climate

16.3.1 Changing Hurricane and Risks in Changing Climate

In this section, the risk-informed decision framework introduced in Sect. 16.2 is illustrated with an example of retrofitting residential buildings located in Miami-Dade County against increasing risks from hurricanes. This example was previously studied by Bjarnadottir et al. (2011). Hurricanes are one of the most catastrophic natural hazards in the world. The U.S. has experienced significant economic losses caused by hurricanes in recent years, including Hurricane Katrina (2005) and Hurricane Sandy (2012), which are ranked at the second and the sixth most costly natural disasters in the world since 1950, respectively (Knabb et al. 2005; Blake and Gibney 2011; Aon Benfield 2013; Blake et al. 2013). While managing risks of the built environment against hurricanes is an important concern of government and private sectors such as insurance industry, risk management of the built environment is complicated because the occurrence and development of a hurricane is impacted by several atmospheric and oceanic dynamics, especially with the consideration of global climate change. Particularly, the trend of climate change is not clearly understood and is often reported contradictorily by various sources. In this work, the uncertainty concerning the risk from hurricanes is used to illustrate the proposed decision-making framework under risk and ambiguity for risk management of civil infrastructure.

Hurricane wind speed is often modeled with the two-parameter Weibull distribution. The wind speed is correlated with annual oceanic temperature change Δ. The probability density function $f_V\left(v, t \middle| \Delta = \delta\right)$ of the wind speed v at year t given the annual temperature change $\Delta = \delta$ (constant over time frame of interest) is then represented as:

$$f_V(v, t|\Delta = \delta) = \frac{a(t, \delta)}{u(t, \delta)} \cdot \left[\frac{v}{u(t, \delta)}\right]^{a(t,\delta)-1} \cdot \exp\left\{-\left(\frac{v}{u(t, \delta)}\right)^{a(t,\delta)}\right\} \tag{16.4}$$

where v is the 3-second (3-s) gust wind speed on open terrain and $v > 0$, $u(t, \delta)$ and $a(t, \delta)$ are the most probable smallest value and the shape parameter at time t given the annual temperature change δ, respectively. For Miami-Dade county, the two parameters of the probability distribution for hurricane wind speed are found to be $u(1, \delta) = 28.89$ and $a(1, \delta) = 1.96$ from 3-s gust wind speed maps (Vickery et al. 2000; ASCE 2010). These parameters correspond to an annual average maximum wind speed of 25.6 m/s and the coefficient of variation of 0.532. In the analysis, annual average maximum wind speed is assumed to change dynamically over time due to the changing oceanic temperature. The tendency of change is reported probabilistically by different scientist groups. We utilize the sample statistics of temperature change that were used in the study by Cameron (2005).[1] For simplicity, we assume that the annual ocean temperature change Δ follows a lognormal distribution. The statistics used in this analysis are:

- The lowest estimation by experts (Expert-lowest): $\mu[\Delta] = 0.0586$ °C/year and $\sigma[\Delta] = 0.012$ °C/year; and
- The highest estimation by experts (Expert-highest): $\mu[\Delta] = 0.1032$ °C/year and $\sigma[\Delta] = 0.035$ °C/year.

A direct relationship between the increase of ocean surface temperature and the increase of hurricane wind speed is used (Emanuel 2005), which predicts that an increase of temperature by 1 °C results in an increase of the average wind speed by 5 %. The coefficient of variation of the wind speed is assumed to remain constant. Then, the parameter $u(t, \delta)$ in the probability distribution of the wind speed in Eq. (16.4) becomes the only parameter that changes along time and relies on the value of ocean surface temperature change Δ. Our preliminary analysis revealed that the variance of wind speed is very sensitive to the shape parameter a and the probability distribution of wind speed becomes unrealistic if the parameter a also changes.

Assuming that structural capacity is deterministic, hurricane risk measured in terms of the expected loss for a single building in a given year t is determined by

$$E[C_D(g_1, R)]_t = \int_{-\infty}^{\infty} \int_0^{\infty} C_D(v, g_1, R) \cdot f_V(v, t|\Delta = \delta) \cdot f_\Delta(\delta) dv d\delta \tag{16.5}$$

where $C_D(v, g_1, R)$ is the damage cost of a building with strength factor R located in exposure category g_1 subject to the wind speed v, and $f_\Delta(\delta)$ is the probability density function of the annual temperature change.

We adopted a damage model by Huang et al. (2001) to calculate the damage cost C_D. The model is based on the insurance claim data for single-family housing units in southeastern U.S. The damage model originally relates the recorded 10-min average surface wind speed of a hurricane to the damage ratio which is defined as the total amount paid by the insurer versus the total insured value. Using the conversion factor to adjust the 10-min average surface wind speed to the 3-s gust wind speed, the damage cost is represented as

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[1] These statistics are used because the report also includes the information about prior belief, which will be utilized later in the section.

$$C_D(v, g_1, R) = \begin{cases} C_{D0} \cdot e^{0.252 g_1 g_2 v - 10.43} \cdot \dfrac{100 - R}{100} & \text{if } v \leq \dfrac{59.7}{g_1 g_2} - \dfrac{\ln(100 - R)}{0.252 g_1 g_2} \mathrm{m/s} \\ C_{D0} & \text{otherwise} \end{cases} \tag{16.6}$$

where v is the 3-s gust wind speed on an open terrain, g_1 is the gradient-to-surface conversion factor depending on the exposure category, g_2 is the conversion factor for 3-s gust wind speed to 10-min average surface wind speed and 0.7 is used in this analysis (Sparks et al. 1994; Rosowsky et al. 2001; ASCE 2010), C_{D0} is the insured value of a residential building and R is a factor that takes into account the differences in the strength of individual building.

For a regional hurricane risk assessment, we categorize the building inventory based on their construction year and location similar to the study conducted by Bjarnadottir et al. (2011). For hurricane risks, the location of a building is related to the characteristics of ground surface irregularities at which the building is constructed, which determines the exposure category. The discount rate is assumed to remain constant at 3 % in the calculation of the expected total cost over a time period T in this study.

16.3.2 Life Cycle Cost Analysis and Risk-Informed Decision Framework for Built Infrastructure Under Ambiguity

Risk-informed decision-making requires identification and analysis of a risk and establishment of robust decision support system. Life cycle cost (LCC) has been used as a common measure of the potential risk for built infrastructure subjected to natural and man-made hazards in recent decades (Frangopol 2011; Kumar and Gardoni 2014). The LCC is defined as the sum of all costs accrued in the service period (T) of the infrastructure of interest, including initial cost (C_I), damage and repair cost (C_D), maintenance cost (C_M), salvage cost (C_S), indirect economic losses (C_E), etc. Assuming maintenance and salvage costs are minor contributors, the expected LCC of a building structure with engineering design parameter vector X is written in a simple form as (Wen and Kang 2001; Ellingwood and Wen 2005)

$$E[LCC(t, \mathbf{X})] = C_I(\mathbf{X}) + E[C_D(\mathbf{X})] \tag{16.7}$$

where initial cost C_I is deterministic in general, and the determination of the expected value of damage and repair cost C_D introduces the major components of uncertainties in the LCC, such as hazard intensity and occurrence, structural capacity, and damage states. If CPT is applied for decision-making, the expected value of C_D at time t is determined as

$$E[C_D(X, Y)]_t = \iint C_D(X, Y) \cdot c_X(x, t) \cdot c_Y(y, t) dx dy \tag{16.8}$$

where X is a random structural capacity parameter, Y is a random demand parameter, $c_X(x,t)$ is the capacity function of X defined by Eqs. (16.2) or (16.3), and similarly $c_Y(y,t)$ is the capacity function of Y. If no ambiguity exists, the capacity functions degenerate to the probability density function of X and Y.

In the decision-making framework based on LCC analysis, a regional hurricane risk is determined by combining the expected damage and repair costs of buildings located in the region. For a simplification of analysis, we used categories of the building inventory based on their construction year and location. The construction year of a building is related to a structural vulnerability since structures that were built in the same period tend to be designed according to the same design code, which satisfy the same design requirements of the resistance to a load. The location of a building is related to the characteristics of the load in general. Then, the expected total damage and repair cost for a region at time t is

$$E\left[C_{D,total}\right]_t = \sum_{i=1}^{N_r} \sum_{j=1}^{N_e} n_{ij} \cdot E\left[C_D(Y(j), X(i))\right]_t \tag{16.9}$$

where N_r is the total number of construction year categories of the building inventory, N_e is the total number of exposure categories in the region, n_{ij} is the number of buildings constructed in the ith construction era and located in the jth site, $Y(j)$ is a demand parameter corresponds to the jth site, $X(i)$ is a structural capacity parameter for a building constructed in the ith construction era. Risk assessment is often conducted over a time period to evaluate the cost effectiveness of different adaptation strategies. If a retrofit option has an implementation cost of C_I, the expected total cost over a time period T associated with the option is

$$E\left[LCC_{Total}(T)\right] = C_I + \sum_{t=1}^{T} E\left[C_{D,total}\right]_t \cdot \frac{1}{(1+\gamma)^t} \tag{16.10}$$

where γ is the discount rate.

16.3.3 Regional Risk Management of Residential Buildings Exposed to Risk from Hurricanes in Changing Climate

For a regional hurricane risk assessment, the building inventory is categorized based on their construction year and location similar to the study conducted by Bjarnadottir et al. (2011). For hurricane risk, location of a building is related to the characteristics of ground surface irregularities at which the building is constructed, which determines the exposure category. Discount rate is assumed to remain constant at 3 % in the calculation of the expected total cost over a time period T in this study (Bjarnadottir et al. 2011).

We classify the buildings located in the region into four groups based on the construction years: (1) pre-1970; (2) 1970–1985; (3) 1986–1997; and (4) post-1998. For each group, the strength factor R is assumed to be—15 %, 0 %, 20 %, and 30 %, respectively. Three exposure categories are considered, which are (1) foreshore; (2) within 10 km from the shore; and (3) further than 10 km. For each exposure category, the value of g_1 is assumed to be 0.9, 0.8, and 0.72, respectively. The similar categories have been used in earlier studies (Jain and Davidson 2007; Pinelli et al. 2009; Bjarnadottir et al. 2011). The total number of residential buildings located in Miami-Dade County is estimated as 991,372 in 2012 (US Census Bureau 2012). Among all the residential buildings, single-family houses have been reported to be the majority of hurricane damage (NAHB 1993) and thus the regional risk assessment will be conducted only for the single-family houses in this study. The median of insured value of a single-family house in the county is used as the value of C_{D0} in the analysis, which is estimated to be \$147,000 in 2009 U.S. dollars (Huang et al. 2001; Zigomanis 2007; Bjarnadottir et al. 2011). The proportion of single-family houses is estimated to be 53 % of all residential buildings in 2008 (Moreno et al. 2008). The department of planning and zoning in Miami-Dade County reported that approximately 42 %, 30 %, 17 %, and 11 % of the residential buildings in 2000 are built before 1970, between 1970 and 1985, between 1986 and 1997, and after 1998, respectively (2003). It is also reported by the department that 20 %, 60 %, and 20 % of the residential buildings in 2000 are located within 1 km of the shore, within 10 km of the shore, and further than 10 km from the shore, respectively (Miami-Dade DPZ 2003). The ratios provided above are assumed to remain constant throughout the years considered in this analysis.

In this study, two adaptation strategies are considered: (Option 1) strengthening the buildings constructed before 1970 at high vulnerability locations, and (Option 2) strengthening all the buildings constructed before 1970. For both strategies, R-value is assumed to increase to 30 %. Three cases are assumed for the implementation cost of the strategies: (C1) 20 %, (C2) 50 %, and (C3) 150 % of insured value per house. Pinelli et al. (2009) reported that the retrofit cost for existing gable roof timber residential buildings constructed before 1970 in Florida is about 15–25 % of the replacement value. Thus, the assumption of 20 % of the insured value for a house as the implementation cost of regular retrofit is reasonable. The value of 50 % represents a higher cost of special retrofit. The highest value of 150 % represents the extreme case of demolishing and rebuilding a structure. The expected total cost is determined by Eq. (16.10) and is listed in Table 16.1. When the retrofit cost of 20 % is assumed, the LCC analysis based on the two different expert predictions (Expert-lowest and Expert-highest) of the climate trend delivers the same conclusion of the optimal strategy with the lowest cost, which is Option 2. When the retrofit cost increases to 50 % of the insured value of a house, the optimal adaptation strategy is found to be different for the lowest and the highest ocean temperature change scenarios, which are Option 1 and Option 2 respectively, as shown in Table 16.1.

Table 16.1 50-year life cycle cost of retrofit options under different assumptions on climate change trend for different retrofit costs

	50-year life cycle cost ($billion)		
	Status quo	Option 1	Option 2
(Case C1) retrofit cost: 20 % of the insured value of a house			
Expert-lowest	38.0	32.9	28.8
Expert-highest	49.1	42.6	36.5
(Case C2) retrofit cost: 50 % of the insured value of a house			
Expert-lowest	38.0	34.2	35.3
Expert-highest	49.1	43.9	43.0
(Case C3) retrofit cost : 150 % of the insured value of a house			
Expert-lowest	38.0	38.6	56.9
Expert-highest	49.1	48.2	64.6

Similarly, the optimum strategy is the status quo and Option 1 corresponding to the two scenarios, respectively, when the cost is assumed to be 150 %.

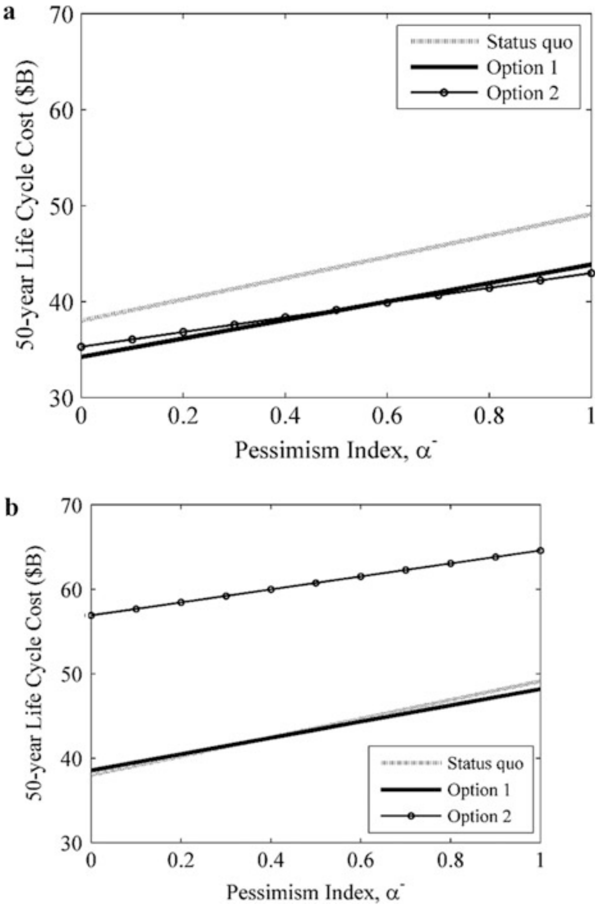
For case C1 with the retrofit cost of 20 %, the LCC analysis delivers the same conclusion of the optimal risk management strategy among the three when the lowest and highest expert predictions of ocean surface temperature changes are incorporated. Therefore, the decision of choosing Option 2 is straightforward, even with the uncertainty or ambiguity associated with probability distributions. However, for cases C2 and C3, different optimal strategies are yielded for the different predictions of ocean surface temperature changes. Additional efforts are required in decision-making given the ambiguity associated with the probabilities. We first use the combination rule defined in Eq. (16.2) to derive the capacity that is used in LCC analysis. The resulting LCCs with the pessimism index α^- varying between 0 and 1 are shown in Fig. 16.1a, b. In the figures, the final optimal strategy is observed to be the same as the optimal strategy supported by the optimistic forecasting of the changing climate when the value of the pessimism index, α^-, is close to zero and changes to the optimal strategy supported by the pessimistic forecast as the value increase to 1. The threshold value of the pessimism index α^- where the optimal strategy switches from Option 1 to Option 2 is found to be 0.55 for case C2. The threshold value of α^- where the optimal strategy changes from status quo to Option 1 is 0.38 for case C3.

To further incorporate individual prior beliefs and illustrate the belief updating process as in Eq. (16.3), we assume the prior belief of a decision maker on the annual ocean temperature change Δ as:

- Prior belief: $\mu[\Delta] = 0.0713$ °C/year and $\sigma[\Delta] = 0.065$ °C/year.

The same sample statistics were used by Cameron (2005). The 50-year LCC for this scenario is found to be $42.7 billion, $38.3 billion and $38.6 billion for Status quo, Option 1, and Option 2, respectively. The confidence index $\beta^- = \beta^+ = \beta$ varies between 0 (the weakest confidence on individual's own belief) and 1 (the strongest confidence on individual's own belief). Figure 16.2a, b show the result of

Fig. 16.1 50-year life cycle cost of retrofit options considering individual's pessimism level: (**a**) case C2, and (**b**) case C3



LCC analysis for the confidence index, β, fixed at 0.5 and 0.1, respectively, for case C2. When $\beta = 1$, the expert's predictions on uncertainty is completely ignored and the results of LCC analysis are exactly the same as that of individuals without the information of experts' opinions. Since a decision maker makes a decision based only on his/her own belief, any inconsistency that is present in experts' opinions affects neither the risk assessment nor the final decision. On the contrary, when $\beta = 0$, the decision maker completely relies on the experts' opinions for decision making, which leads to the same decision as the one in Fig. 16.1a. When $\beta = 0.5$, the decision maker gives equal weights on his/her own belief and the information provided by experts. As β increases, the threshold value of α^-, where the life cycle cost curves cross over and the optimal strategy changes from Option 1 to Option 2, increases, which suggests that the prior belief of the decision maker in the example is closer to the optimistic prediction of experts. The trends of the threshold values of α^- at the cross-over are shown in Fig. 16.3 for cases C2 and C3. It is seen that the trends for the two cases are different. For the extremely high retrofit cost, as

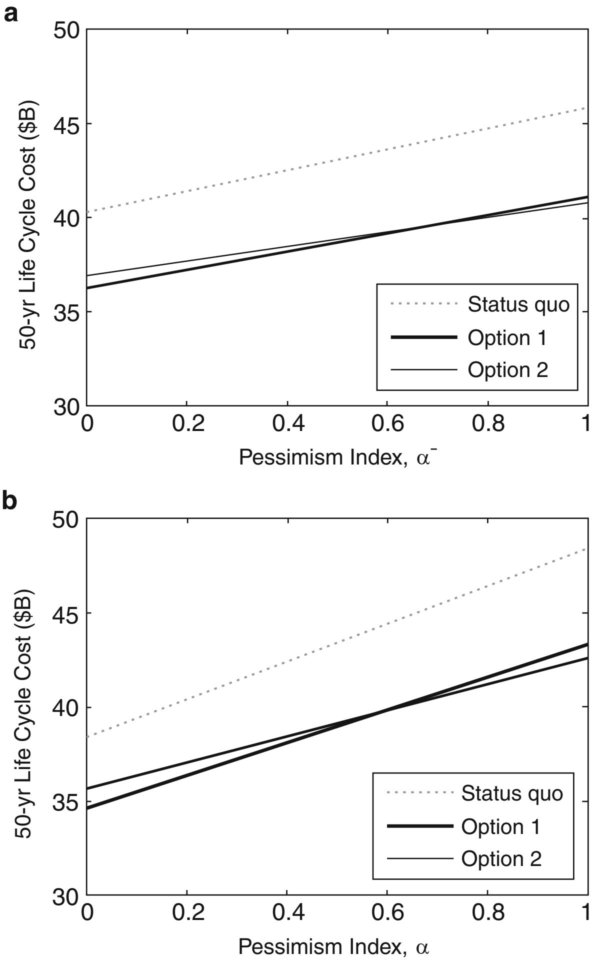


Fig. 16.2 50-year life cycle cost of retrofit options considering individual's pessimism and confidence level: (**a**) $\beta = 0.5$ and (**b**) $\beta = 0.1$

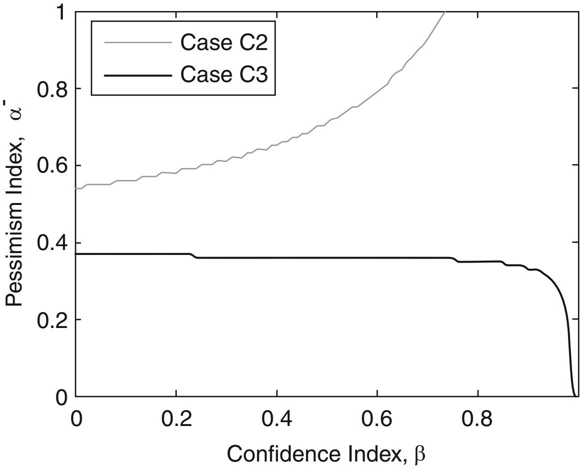


Fig. 16.3 Cross-over point of α^- in which the optimum options switch

in case C3, the decision maker's prior belief does not have much influence on the optimum decisions, given the relatively flat curve in Fig. 16.3, unless he/she has a very strong opinion with the value of β. In contrast, the optimum decision more sensitively depends on the decision maker's confidence when the retrofit cost reduces.

16.4 Concluding Remarks and Future Extensions

Risk-informed decision making for civil infrastructure is particularly influenced by risk perception and attitude of the public, because of the direct impact of infrastructure failures as well as possible casualties to the function of a society. Risk management thus requires a thorough understanding of how it is perceived by the stakeholders as well as understanding of its components of risk (likelihood and consequence). Both risk and ambiguity attitudes need to be incorporated in decision-making, especially when uncertainties prevail in assessing both of risk components. In this chapter, a new risk-informed decision making framework under ambiguity is proposed, with a new method to model risk and ambiguity attitudes of a decision maker when there exists imprecision in probability estimation, utilizing belief update and cumulative prospect theory. To illustrate the proposed methodology, risk mitigation decisions for residential buildings that are exposed to increased risks of wind hazards in changing climate are investigated in the chapter. The study revealed that there is a potential discrepancy of decisions between the projected risks of the climate change scenarios. The discrepancy also leads to a potential shift of the optimal risk mitigation strategy, sensitively depending upon the risk perception of the decision maker when the information of risk and ambiguity attitudes is provided. The framework developed in this study can be utilized to advance public decision making in the presence of uncertainty and lack of information.

In current work, the sensitivity of risk-informed decisions with respect to risk and ambiguity attitudes is studied, including the values of pessimism and confidence indices. Further studies of how risk perception of a specific hazard would have influences on decision-making processes can provide more details of risk-informed decision making for civil infrastructure. Furthermore, various assumptions of probability distributions were made in this study. More research of how to effectively elicit probability as well as risk attitude and ambiguity attitude for the proposed framework is needed.

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Chapter 17
Societal Perspective in Risk Management: Application of Life-Quality Index

Mahesh D. Pandey and Neil C. Lind

Abstract Risk can always be reduced but at some cost. Since disproportionate cost of risk reduction diverts societal resources away from other critical needs, efficiency argument has been enshrined in regulatory practices worldwide. This means the benefits of improved safety must be balanced against the cost of risk reduction. Aging and degradation of infrastructure facilities and systems have raised concerns over the safety of public, environment and economic productivity. Large investments are required to upgrade civil and industrial infrastructures in compliance with safety regulations. The chapter presents the Life Quality Index (LQI) formulation to assess the effectiveness of regulations and infrastructure projects that have major impact on life safety.

17.1 Introduction

"How safe is safe enough?" This basic question has inspired quantitative evaluation of risk to rationalize regulations and engineering standards that aim to reduce risk in society. Experience-based professional judgment has always been fundamental in public risk management, health care, and engineering. Professional practice is now moving towards objective, transparent and accountable management of risks at the societal level. In addition to scientific evaluation of risks, an understanding of acceptable level of risk is equally important—more so, because it provides a basis to prioritize and invest in risk management programs.

In order to establish a threshold of acceptable risk, the key issues that need to be addressed are how to (1) choose a standard of what the associated risks are worth and assure that it serves society; (2) allocate limited resources for life-saving

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purposes for the collective benefit of society; (3) ensure transparency of the decision-making process; and (4) maintain respect for societal values. There is a considerable body of literature that explores the principles of managing risk in public interest and basis for determining the acceptable risk, as reviewed by Murphy and Gardoni (2007, 2008). This chapter does not review different methods of determining the acceptable risk, rather it focuses on one particular approach that relies on the social indicator to assess the impact of risk on society and measures to mitigate such risks.

Inspired by the Human Development Index (UNDP 1990), a new social indicator, Life Quality Index, was developed which has two component, namely, the life expectancy and the gross domestic product (GDP) per person (Pandey et al. 2006). The LQI can also be interpreted as an ordinal utility function that quantifies the utility of income derived over the expected lifetime of a representative individual in the society. It comprises of economic, demographic and life-safety aspects of a society (Nathwani et al. 2009).

The chapter illustrates the derivation of a minimum acceptable limit of resources that the society should commit to risk reduction in a sustainable manner. The key idea is that the engineered safety should be determined on the basis of a balance between the cost of risk control measures and the benefits in terms of improving life safety. This approach is analogous to a cost-benefit analysis that relies on LQI. The chapter clarifies the underlying concepts, computational procedures and provides the interpretation of results so that engineers can apply this method to practical examples of risk management.

The LQI approach is applied to assess the benefits of the Quantitative Health Objectives (QHOs) adopted by the U.S. Nuclear Regulatory Commission to control the risk of radiation exposure. The other potential area of application is the allocations of resources to infrastructure renewal projects. The safe and efficient management of engineering infrastructure systems, such as power plants, pipelines, transmission lines, bridges, highways, water distribution and waste-disposal systems, directly contributes to economic well-being and quality of life in the society.

17.2 Life Quality Index

17.2.1 General Concept

Maximizing a utility function has been a traditional approach to optimizing decisions. This approach can be extended to societal risk management. Longevity and quality measured by social income are two key determinants of life quality, among many other possible attributes that matter to life quality. A societal utility function, referred to as Life-Quality Index, is postulated that consists of life expectancy and the gross domestic product (GDP) person.

LQI is an ordinal utility function that quantifies the utility of income derived over the potential lifetime of a representative individual in the society (Pandey and Nathwani 2003a, c, 2007). The LQI has been derived as (Pandey et al. 2006)

$$L = cg^{q}e \leq \tag{17.1}$$

where e, g and c are the life expectancy, GDP per person and a constant, respectively. The parameter q has especial significance as it reflects a trade-off that the society places between economic consumption and the value of the length of life. Using macroeconomics theories, the exponent was derived as (Pandey et al. 2006)

$$q = \frac{1 \quad w}{\beta(1 - w)} \tag{17.2}$$

In this expression, β denotes the share of labor input (i.e., wages) to GDP and w is the work time fraction in a year. Although a formal derivation, interpretation and calibration of the LQI have been presented elsewhere (Pandey et al. 2006), an example of LQI calibration is presented in Sect. 17.3.

17.2.2 Illustration of LQI Calibration

In this section, the calibration of LQI using the Canadian economic and demographic data is illustrated. For Canada, the time series for the period 1961–2003 were used and all economic data were standardized in constant 1997C$ (Statistics Canada, www.statscan.ca).

Figure 17.1 shows the trend of increase in the Canadian population from 18.2 million in 1961 to 31.6 million in 2003. The workforce increased from 6.4 to 15.9 million in the same period. The ratio of the workforce to population has increased from 35.6 to 50.5 % in this period. Figure 17.2 shows that the GDP per person (in 1997 CAD $) has increased from $13,456 in 1961 to 34,675 in 2003, whereas the GDP per worker has grown from $27,839 to $68,632 in the same period.

The historical trends of the labor or work time fraction per year per person (w) used in producing the GDP is shown in Fig. 17.3. The work time fraction for workers is calculated from the average number of hours worked per employed person/year, estimated from labor market surveys. The work time fraction at the population level is obtained as the total number of work hours divided by the national population.

According to Cobb-Douglas production theory, the ratio of wage to GDP is a measure of the share of labor coefficient, β, in the production function (Nathwani et al. 2009). This ratio is plotted in Fig. 17.4, which shows a stable trend for Canada within the limits of 0.5–0.55.

To calculate q, the work time fraction (w at population level) from Fig. 17.3 and wage to GDP ratio (β) from Fig. 17.4 were substituted into Eq. (17.2). The resulting

Fig. 17.1 Increase in the Canadian population and workforce (1961–2003)

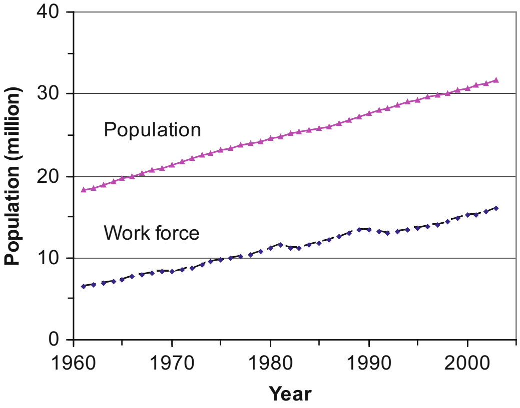


Fig. 17.2 GDP per person growth in Canada (1961–2003)

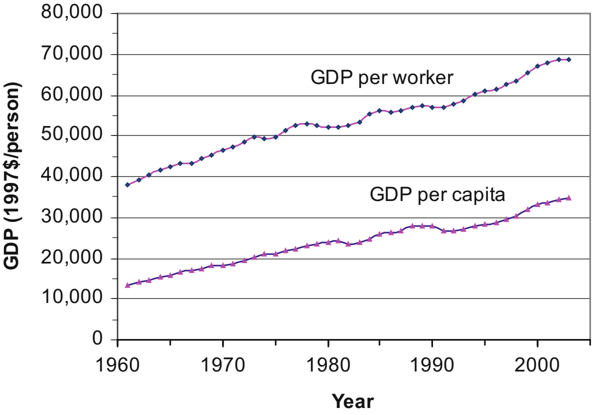
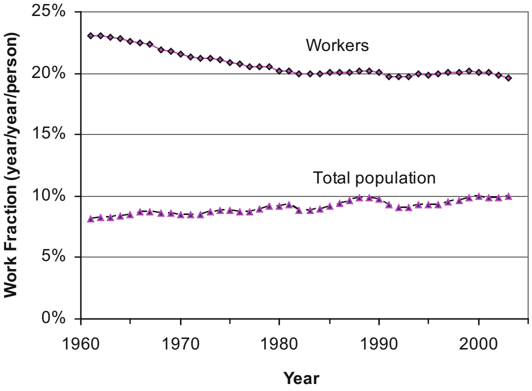


Fig. 17.3 Annual work time fraction in Canada (1961–2003)



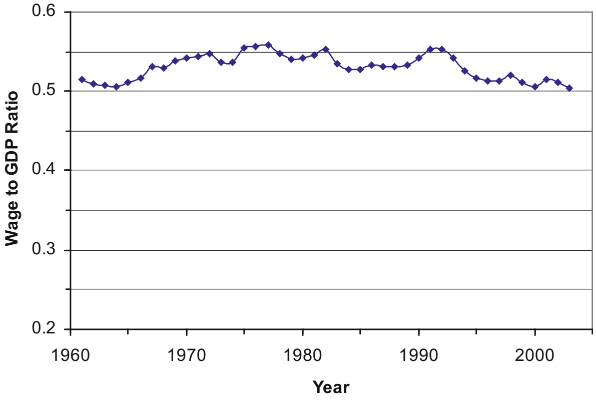


Fig. 17.4 The ratio of wage to GDP in Canadian economy

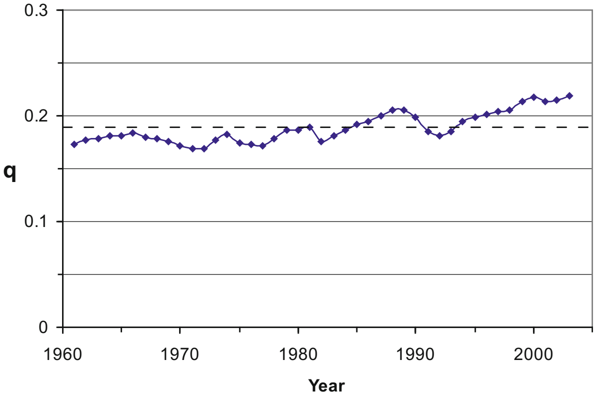


Fig. 17.5 The historical trend of the LQI exponent (q) based on the Canadian data

time series plotted in Fig. 17.5, shows that q varies in a narrow range of 0.17–0.21 with an average value of 0.19.

Given a small fluctuation in q, a mean value of $q = 0.2$ can be used in practical applications. The constant of proportionality, c, is not relevant to cost-benefit analysis. The LQI coefficient was also calculated for several OECD countries, which showed that q varies between 0.15 and 0.2 (Pandey et al. 2006).

The calculation of LQI can be illustrated using some practical data. The life expectancy at birth in Canada for example is 77.5 years. Assuming a value of the real GDP per capita as $g = 30{,}000$ \$/person/year, the LQI is computed as $(30{,}000)^{0.2} \times (77.5) = 609$ utils (note that utils are arbitrary units of the utility function which has no physical meaning).

17.2.3 Life Expectancy and Related Concepts

Define the probability density function of the lifetime, T, as $f_T(t)$, and use a concise notation to denote it as $f(t)$. In general, the life expectancy (i.e., the expected time of remaining life from the present) at birth is defined as

$$e = \int_0^{a_u} t f(t) dt = \int_0^{a_u} S(t) dt \tag{17.3}$$

where a_u is some maximum value of the human lifetime (≈110 years) and $S(t)$ is the probability of survival up to age t, which can be defined in terms of the lifetime density and mortality rate, $m(t)$, as

$$S(t) = \int_0^{t} f(\tau) d\tau = \exp\left[- \int_0^{a} m(\tau) d\tau \right] \tag{17.4}$$

Survival probabilities for different ages are described in an actuarial life table for a country. The current survival and hazard (or mortality) curves for Canada are shown in Fig. 17.6.

The life expectancy (i.e., the expected time of remaining life) changes with the age of the person. To illustrate this, the conditional probability density function of the lifetime of a person surviving up to age a is introduced as

$$f_T(t|T > a) = \frac{f(t)}{P[T > a]} = \frac{f(t)}{S(a)} \tag{17.5}$$

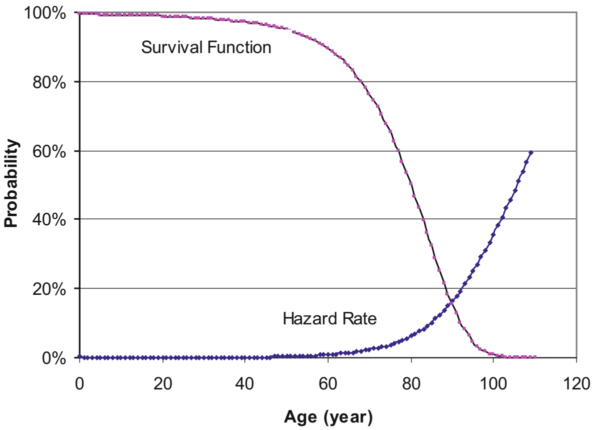


Fig. 17.6 Survival function and hazard rate of the human lifetime

The remaining life expectancy of a person of age a is denoted as $e(a) = E[T - a| T > a]$. This is equivalent to average remaining life of a person of age a.

$$e(a) = E\left[T - a\middle|T > a\right] = \int_{a}^{a_u} (t - a) f\left(t\middle|T > a\right) dt = \int_{a}^{a_u} (t - a) \frac{f(t)}{S(a)} dt$$

$$= \int_{a}^{a_u} \frac{S(t)}{S(a)} dt \tag{17.6}$$

The ratio of survival probabilities in Eq. (17.5) can be expressed in terms of the mortality rate as

$$\frac{S(t)}{S(a)} = \frac{\exp\left[-\int_{0}^{t} m(\tau) d\tau\right]}{\exp\left[-\int_{0}^{a} m(\tau) d\tau\right]} = \exp\left[-\int_{a}^{t} m(\tau) d\tau\right], \qquad 0 \le a \le t \tag{17.7}$$

Substituting Eqs. (17.6) into (17.5) leads to

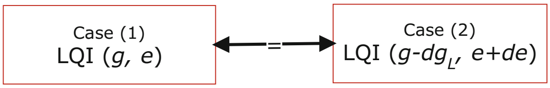
$$e(a) = \int_{a}^{a_u} \exp\left[-\int_{a}^{t} [m(\tau)] d\tau\right] dt \tag{17.8}$$

If the mortality rate is changed from $m(\tau)$ to $[m(\tau) + h(\tau)]$, it would modify the lifetime distribution. The modified distribution can be denoted by a new random variable T_1 and the mean lifetime can be obtained as

$$e_1(a) = \int_{a}^{a_u} \exp\left[-\int_{a}^{t} [m(\tau) + h(\tau)] d\tau\right] dt \tag{17.9}$$

The change in life expectancy is the average change in lifetime estimated as $de = \mathrm{E}[T - T_1] = (e - e_1)$. It should be noted that a change in mortality rate at any age $t \ge a$ will influence the remaining life expectancy, and the change in life expectancy is an average quantity that occurs over the lifetime of an individual.

Fig. 17.7 LQI invariance principle



17.2.4 Benefit-Cost Analysis Using LQI

One important goal in managing risks to life safety is to determine a minimum acceptable level of expenditure that can be justified on behalf of the public in exchange for a small reduction in the risk of death without compromising the life-quality. It can also be referred to as the societal capacity to commit resources (SCCR) and it can be obtained from the LQI invariance criterion as follows.

Suppose that a risk management program has a potential to improve the life expectancy from a reference or baseline level of e to $(e + de)$. A threshold value of the cost of the program, dg_L (in \$/year), can be calculated from the invariance criterion such that LQI in the reference case (g, e) is the same as in the new scenario $(g - dg_L, e + de)$, as shown in Fig. 17.7. This condition can be expressed as

$$\frac{dL}{L} = 0 \Leftrightarrow \frac{dg_L}{g} + \frac{1}{q}\frac{de}{e} = 0 \tag{17.10}$$

A threshold value of the cost rate can thus be derived as

$$(-dg_L) = \frac{g}{q}\frac{de}{e} \quad (\$/\text{person}/\text{year}) \tag{17.11}$$

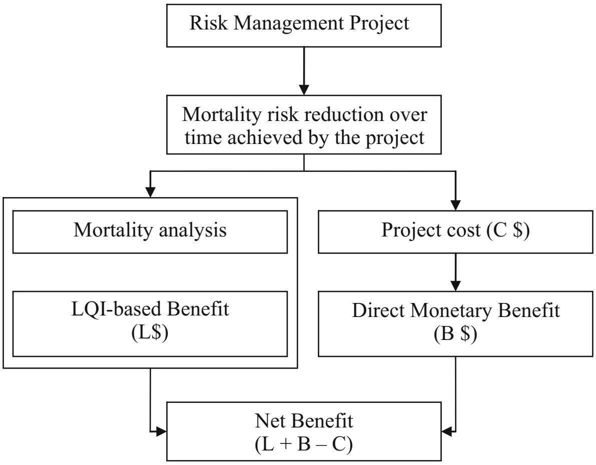
17.2.5 Societal Capacity to Commit Resources (SCCR)

A careful interpretation of all the terms in Eq. (17.10) is important. If the risk management program results in a gain in life expectancy, dg_L represents the maximum allowable cost per year to fund the program. In other words, if the actual program cost rate is less than dg_L, the program improves the LQI for the population under consideration. If a project results in loss of life expectancy, then dg_L represents minimum benefit that should be derived from the project. Otherwise, it will result in a decrease in the LQI.

It is noteworthy that $e \times dg_L$ is the amount per person that society should gain as a result of a risky project that imposes an additional risk that reduces person's life expectancy by de. Conversely, $e \times dg_L$ is the amount per person that society should spend in a project that improves the life expectancy by de. This threshold amount is referred to as the Societal Capacity to Commit Resources (SCCR) (Nathwani et al 2009). This value is specific to a society since it depends on the background mortality, demographics, and economic development.

The term de/e is in the unit of life years gained (or lost) per year of lifetime. The maximum cost of saving one life year can then be computed from Eq. (17.10) as

Fig. 17.8 Benefit-cost analysis using LQI method



$$\frac{(-dg_L)}{de/e} = \frac{g}{q} \quad \{(\$/\text{year})/(\text{life year}/\text{year}) \ = \ \$/\text{life year}\} \tag{17.12}$$

For $g = 30{,}000$ and $q = 0.2$, this value is 150,000 $/life year saved. This value is independent of the age of the person.

Another interesting quantity is dg/de, which is interpreted as the cost rate in $/year for saving one life year:

$$\frac{(-dg_L)}{de} = \frac{1g}{qe} \quad (\$/\text{year}/\text{life year}) \tag{17.13}$$

In summary, so long as the cost rate of implementing a program is less than that given by Eq. (17.10), the program can be considered to be beneficial from the LQI point of view.

A schematic of the LQI method is presented in Fig. 17.8. It should be recognized that a key input to LQI method is the change in mortality rates due to proposed project. Subsequently, it is important to quantify a change in life expectancy correctly. If a project has no impact on life safety, only an economic cost-benefit analysis is needed to judge its acceptability.

17.3 Applications

17.3.1 A Hypothetical Example

To illustrate the LQI method, we consider a hypothetical example of an infrastructure system to control environmental pollution. The inspection and surveillance data indicate that the system is experiencing increasing deterioration over next

40 years. If the system is not refurbished, it would pose a public hazard, which would increase the mortality rate in the exposed population. To deal with this situation, a refurbishment project is proposed to mitigate the impact of this hazard over a 40-year period. A key question in the decision-making process would be: what is the acceptable cost of this project? The LQI method can help answer this question.

17.3.1.1 Analysis

For the clarity of illustration, consider that only persons of age 50 years are affected by this hazard. The remaining life expectancy at age 50 is 29.9 years, which is estimated from a truncated remaining lifetime distribution, $f_{50}(x) = f(x)/S(50)$, as shown in Fig. 17.9.

Figure 17.10 illustrates calculation of the LQI as an integration of the utility of income derived over the remaining lifetime of a 50-year-old person:

$$LQI(50) = \int_{50}^{110} U(G) f_T\big(x \big| x > 50\big) dx = \int_{50}^{110} G^q \frac{S(x)}{S(t)} dx = G^q e(50) \qquad (17.14)$$

Thus,

$$LQI(50) = (30,000)^{0.2}(29.9) = 235\,\text{utils} \qquad (17.15)$$

As stated earlier, the deterioration of infrastructure system increases the mortality risk, which is described as $m_{new}(k) = m_{old}(k)\ (1 + r(k))$, $50 \le k \le 90$. For illustration purposes, it is assumed that $r(k)$ increases linearly from 0.05 to 0.15 beginning from age 50 to 90 year. Note that an exaggerated mortality risk due to deterioration is considered for illustrative purposes only. In practical cases, very

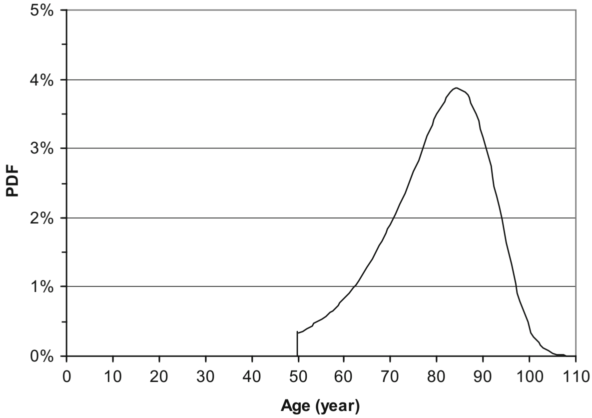


Fig. 17.9 The remaining lifetime distribution of the person of age 50 years

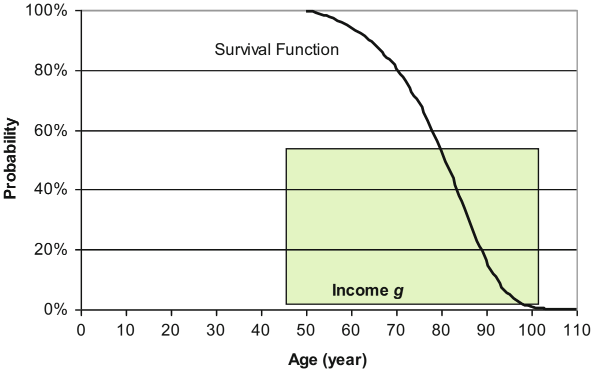


Fig. 17.10 Computation of LQI for the person of age 50 years

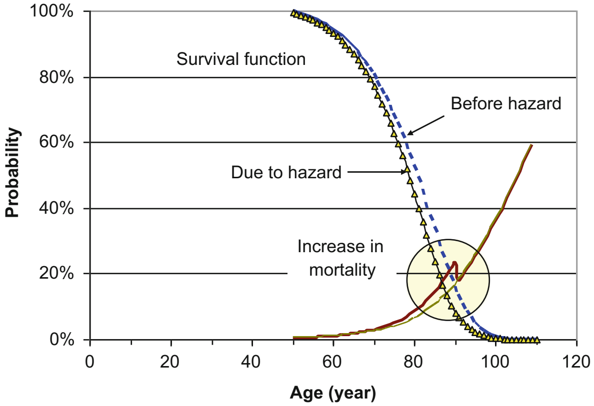


Fig. 17.11 The impact of increased mortality rate for the person of age 50 years

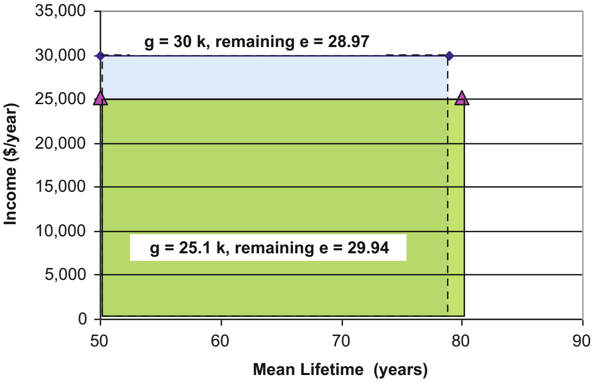
small changes in life expectancy are seen. Another remark is that the assessment of increased hazard and its mortality impact are not trivial tasks. Comprehensive scientific modeling and analysis are required to achieve this work. This information is a critical input to the LQI model.

An effect of increased mortality rate on the survival curve is illustrated in Fig. 17.11. The new survival curve is obtained by modifying the hazard rates between 50 and 90-year ages. In presence of the new hazard, the life expectancy is reduced to 28.97 years from the original value of 29.94 year. These calculations are done using a simple spreadsheet package and the Canadian life table.

The infrastructure refurbishment project is intended to remove the effect of deterioration. In other words, an anticipated gain in life expectancy due the project is $de(50) = 29.94 - 28.97 = 0.97$ year. The LQI threshold cost rate for this project can be estimated from Eq. (17.10) as

$$(dg_L) = \frac{g}{q}\frac{de}{e(50)} = \frac{30,000 \times 0.97}{0.2 \times 29.94} = 4860 \tag{17.16}$$

Fig. 17.12 Illustration of LQI invariance principle



In summary, there are two scenarios. First is "do-nothing" scenario in which life expectancy would reduce to 28.97 years, but the income would remain unaffected at $g = 30{,}000$ $/year. The other scenario is to restore LE to 29.94 years, but the income would change to $(g - dg) = 30{,}000\text{–}4860 = 25{,}140$ $/year. The LQI would remain the same in both scenarios, as shown in Fig. 17.12.

The cost rate per life-year saved is calculated as

$$\frac{dg}{de} = \frac{4860}{0.97} = 5010\ \$/\text{year}/\text{lifeyear saved} \tag{17.17}$$

The maximum total cost of this project is given as $L = 4860 \times 29.94$ year $= 145{,}508$ $/person. In other words, the project is beneficial from LQI criterion so long as its total cost is less than 145,508 $ per exposed person.

If the exposed population consists of persons of other age groups, this analysis needs to be repeated for each age group and the results have to be summed over the age distribution. In the calculations presented here, the discounting is not taken into account. For more details of these topics and LQI applications to structural engineering, readers are referred to Rackwitz et al. (2002, 2003, 2005).

17.3.2 Analysis of Radiation Safety Regulations

The qualitative safety goals adopted by the U.S. NRC (2001) are as follows:

Firstly, individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health. Secondly, societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks. To achieve these objectives, NRC adopted two Quantitative Health Objectives (QHOs), which are analyzed in this section using the LQI framework.

17.3.2.1 QHOs of the U.S. NRC

The first QHO is related to prompt fatality and states that the additional risk should not exceed 0.1 % of the total prompt fatality risk to the population. The baseline risk of prompt fatality in the U.S. was estimated as 5×10^{-4} per year. Thus, the maximum risk imposed by the nuclear power plant is allowed to be 0.1 % of the baseline value, or 5×10^{-7} per year.

Using the life table analysis, reduction in life expectancy at birth due to this risk is estimated as $de = 13$ h. The LQI equivalent impact is estimated using Eq. (17.10) as $dg = 3.5$ $/person/year (=260 $/person). Impact of additional risk indeed appears to be insignificant.

The second QHO related to cancer fatality states that risk should not exceed 0.1 % of the total cancer fatality risk to the population from all other causes. The baseline risk of cancer fatality in the U.S. population is 2×10^{-3} per year per person. As per QHO-2, a maximum risk imposed by the nuclear power plant is allowed to be 2×10^{-6} per year. The loss of life expectancy at birth due to this risk is estimated as $de = 52$ h per person. The LQI equivalent monetary impact is estimated as $dg = 14$ $/person/year (=1042 $/person). This computation ignores the delayed onset of cancer mortality.

17.3.2.2 Dollar Per Person Rem

US NRC (1995) has recommended 2000 Dollar per person-rem as a threshold value for investing in radiation reduction equipment and program. Note that “rem” is a unit of effective absorbed dose of ionizing radiation in human tissue, equivalent to one roentgen of X-rays. The dollar per person rem limit means that if a program costs more than 2000 $/person rem reduction, it does not pass the benefit cost efficiency test. This limit was estimated as a product of the value of statistical life (VSL) of $3 million with the risk of death of 7×10^{-4} per person-rem.

It is not clear as to exposure being a single event, or it continues permanently over a longer period of time. A reduction in mortality risk of 7×10^{-4} per year over the entire life of a person is quite substantial, as it would increase the life expectancy by 2 years. It is not clear to us whether or not this is the implication of the regulatory limit.

This problem can be approached in a different way. Suppose, a 2000 $/person investment is made in the risk reduction program. The LQI allows to impute a value of minimum risk reduction that ought to be achieved by this investment. The LQI equivalent reduction in risk of death should be 4.5×10^{-6} per person per year, which implies 117 h (about 5 days) of increase in the life expectancy at birth.

17.3.2.3 Fire Risk Reduction Program

In Browns Ferry nuclear plant, over \$80 million were spent to reduce the fire risk causing the core damage (1988). Overall risk reduction achieved by this modification was estimated as 7.8×10^{-5} per year (McCullough and McCullough 1991). This program was effective for remaining 15 year of the plant life.

LQI analysis of this risk reduction can be carried out assuming that average age of the plant worker age was 30 years. Applying this risk reduction a life table analysis, the resulting increase in life expectancy was estimated as 16 days. The LQI equivalent monetary impact is estimated as $dg = 6602$ \$/person/year, which is a rather significant amount. This analysis is also somewhat approximate as the underlying assumptions of core damage frequency analysis are not clear to us. Nevertheless, this example illustrates how one can evaluate the effectiveness of a risk reduction program using the LQI approach.

17.4 Conclusions

It is generally accepted that resources committed to mitigation of risks to the public should be utilized in an efficient manner. However, an absolute and objective definition of efficiency in societal risk management is hard to achieve, and, therefore, some normative guiding principles are needed. A basic goal in risk regulation should be to preserve life in good health and resources. To address this goal, an approach based on the Life Quality Index is proposed.

LQI is a “parsimonious” surrogate for the societal utility function including longevity, and social income are two key factors. The Life Quality Index (LQI) reflects the overall societal valuation of life time and economic activity. The chapter illustrates that the societal capacity to commit resources to risk reduction in a sustainable manner can be derived from the LQI. The chapter presents an exposition of the LQI-based benefit-cost analysis method that can be used to evaluate the impact of safety regulations and investments in risk reduction projects. The chapter derives a maximum cost or minimum benefit threshold to judge the acceptability of a project. The chapter clarifies input requirements, computational steps and how to interpret the results of the analysis in order to facilitate practical applications of the LQI method. The LQI analysis of the Quantitative Health Objectives used by the U.S. NRC is discussed along with the implications of the dollar per rem limit. Other applications of LQI to air quality management and flood risk reduction programs are already presented by the authors (Pandey and Nathwani 2003b; Lind et al 2009).

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