

**INTERDEPENDENCY OF SCIENCE AND RISK FINANCE
IN CATASTROPHE INSURANCE AND CLIMATE CHANGE**

Paul R. Kleindorfer
INSEAD (Fontainebleau);
The Wharton School of the University of Pennsylvania.

Working Paper # 2010-01

Risk Management and Decision Processes Center
The Wharton School, University of Pennsylvania
3730 Walnut Street, Jon Huntsman Hall, Suite 500
Philadelphia, PA, 19104
USA
Phone: 215-898-4589
Fax: 215-573-2130
<http://opim.wharton.upenn.edu/risk/>

THE WHARTON RISK MANAGEMENT AND DECISION PROCESSES CENTER

Established in 1984, the Wharton Risk Management and Decision Processes Center develops and promotes effective corporate and public policies for low-probability events with potentially catastrophic consequences through the integration of risk assessment, and risk perception with risk management strategies. Natural disasters, technological hazards, and national and international security issues (e.g., terrorism risk insurance markets, protection of critical infrastructure, global security) are among the extreme events that are the focus of the Center's research.

The Risk Center's neutrality allows it to undertake large-scale projects in conjunction with other researchers and organizations in the public and private sectors. Building on the disciplines of economics, decision sciences, finance, insurance, marketing and psychology, the Center supports and undertakes field and experimental studies of risk and uncertainty to better understand how individuals and organizations make choices under conditions of risk and uncertainty. Risk Center research also investigates the effectiveness of strategies such as risk communication, information sharing, incentive systems, insurance, regulation and public-private collaborations at a national and international scale. From these findings, the Wharton Risk Center's research team – over 50 faculty, fellows and doctoral students – is able to design new approaches to enable individuals and organizations to make better decisions regarding risk under various regulatory and market conditions.

The Center is also concerned with training leading decision makers. It actively engages multiple viewpoints, including top-level representatives from industry, government, international organizations, interest groups and academics through its research and policy publications, and through sponsored seminars, roundtables and forums.

More information is available at <http://opim.wharton.upenn.edu/risk>.

INTERDEPENDENCY OF SCIENCE AND RISK FINANCE IN CATASTROPHE INSURANCE AND CLIMATE CHANGE¹

Paul R. Kleindorfer²

ABSTRACT

This paper describes the interdependencies of science and risk finance for catastrophe insurance. While the basic arguments here apply to all catastrophe risks, including seismic and terrorism risks, I will focus on risks associated with climate change. This traditional logic of actuarial science is the starting point for the present paper. This logic calls for sound science as the foundation of risk-based rates for insurance and related securitized products anchoring national responses to natural hazards and project financing. Lack of sound science would run counter to objective insurability criteria as well as undermining the identification and implementation of cost-effective mitigation and longer-term adaptation measures. Building on this general line of thinking, the paper explores some additional complexities of science-catastrophe risk linkages related to climate change. These include the sizeable epistemic risks associated with scientific uncertainties surrounding climate change and the implications for choices of owners of vulnerable assets and for uncertainty loadings in insurance contracts and for adaptation measures. I also discuss the consequences of the same scientific uncertainty in exacerbating the problem of communicating an understanding of the financial consequences of climate change risks to policy makers and to owners of assets vulnerable to these risks. Finally, I briefly consider the implications of this discussion for the products and services that a market-oriented private insurer could offer to clients facing climate change risk. The most important new client on the block under climate change will surely be governments, which will face potentially very large new liabilities from climate change. I argue that a continuing close relationship between science and risk finance will be essential to promote viable insurance products for catastrophe risks, whether the risk capital is public or private, as well as an informed public dialog on how to face the increasingly evident risks of climate change.

¹Paper prepared for the Second International Conference on Asian Catastrophe Insurance, 8-9 December 2009, Beijing, China. Parts of this paper are based on my earlier paper Kleindorfer (2009c).

²Paul Dubrue Professor of Sustainable Development and Distinguished Research Professor, INSEAD (Fontainebleau), and Anheuser-Busch Professor Emeritus of Management Science and Public Policy, The Wharton School of the University of Pennsylvania.

Introduction

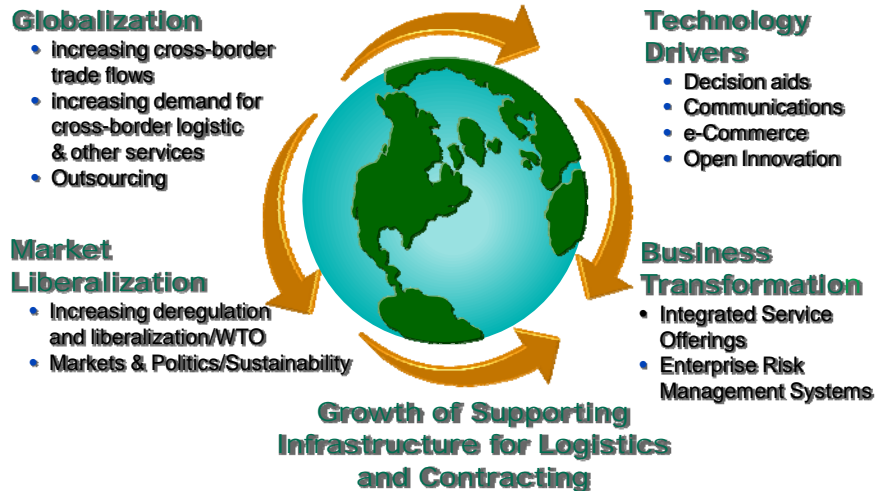
Human activity is putting the future of the planet at risk. The increasingly visible signs of this are everywhere (see Munasinghe, 2009). The most visible of all is population growth, with global population predicted to top 7 billion souls by mid-year 2010. The resulting strain from this population and increasing consumption per capita are also visible. Depletion of cheap resources, including forests and fish populations, are in clear evidence as extraction has exceeded new discoveries or replenishment. Water pollution and droughts are complicating already scarce clean water supplies, with major consequences for households and the agriculture sector. The list of anthropogenic impacts is a long one, and not a very cheery one to contemplate. At the top of this list are Greenhouse Gas (GHG) emissions and the threat of global climate change associated with them.

These events arrive at a time when global economic integration is at a new peak. In the past two decades, the forces and institutions that govern global economic activity have undergone immense changes (see Kleindorfer & Wind, 2009). As shown in Figure 1, these include the ongoing development in liberalization and governance initiated by the World Trade Organization (WTO). Cross-border acquisitions and alliances, together with new markets and new forms of contracting, are supporting outsourcing, unbundling, contract manufacturing, and a variety of other forms of extended-value, network-based constellations. The huge leap forward of the Chinese economy to become a global force for development is one of the strongest signs of this globalization movement. On the market side, the Internet has empowered consumers, driven the creation of electronic markets, including those for insurance products, and in the process has transformed whole industries. In tandem, developments in transportation and integrated logistics providers such as FedEx, UPS, and DHL have revolutionized global fulfillment architectures for business-to-business (B2B) and business-to-consumer (B2C) markets. These changes together have resulted in large increases in international trade from 2000 to 2008 (as shown in Figure 1 in terms of total exports in merchandise and services--M&S in the Figure). For example, Asia booked \$4.353 trillion in the value of its outward merchandise trade flows in 2008, of which China alone was responsible for \$1.428 trillion. All of this spells increasing interdependency and increasing risks from disruptions in the resulting much more integrated global economy.

Growth in International Trade*

Total Exports (M & S) 2000 = \$7.94 Trillion

Total Exports (M & S) 2008 = \$19.86 Trillion



* Figures are in current \$'s. Source: WTO--<http://stat.wto.org/Home/WSDBHome.aspx>; For a discussion, see Kleindorfer and Wind, *The Network Challenge* (2009).

Figure 1: Global Trends Driving Increasing Economic Interdependence

Just as increased population movements to coastal areas increases economic value at risk from storm activity, so too the increased integration of the economic order exposes global supply chains to a greater scope of hazards. Thus, increased global economic integration is itself a first-order effect driving the increase in systemic risks from sea-level rise, increasing storm frequency or virulence and other weather-related risks related to climate change.

For insurers, there will be both increased risks and increased opportunities. Indeed, helping business clients and national governments to assess, mitigate and insure the risks from their increased global exposures is going to be a significant business opportunity for risk management services arising from the threat of climate change. These increased vulnerabilities will require new services and competencies to assist business clients to improve Enterprise Risk Management Systems to manage increased supply chain and facility disruption risks and political risks. Similarly, at the country level, helping national planners to assess and prepare for the financial consequences of larger weather-related risks, and their correlations with other major risks, will be an important area of future risk management services.³ Other opportunities will come in innovations for the new carbon economy and in hybrid adaptation projects, which link risk management with major infrastructure investments

³ For an introduction to country-level risk management, see OECD (2009).

responding to changing water or energy needs. However, climate change is potentially a very large and unpredictable phenomenon and harvesting these opportunities will require the insurance industry to work closely with the scientific community to understand and quantify these risks.

It is important to recognize at the start that climate change necessarily involves the public sector. This is because the temporal reach of market instruments extends at most 10-15 years. Beyond this, the muting effect of discounting associated with capital allocation means that markets alone cannot address response strategies for climate change. Political choices and regulations are required as well. The magnitude of the losses from major climate events also precludes the global insurance and reinsurance industry from financing events in excess of a few 100 billion \$'s, which are within reach of potential climate change events. For example, as noted in Kunreuther and Michel-Kerjan (2009), coastal insured value for the top ten states in the USA accounts for more than \$8.3 trillion, and has been growing in unabated fashion. Thus, notwithstanding the reluctance of many private insurers and reinsurers to see a deep involvement of the public sector in risk management and risk transfer markets, such a role is unavoidable in the climate change area.

The call to action to address climate change was first muted and uncertain. That has changed. Around the world, companies and countries are now deeply engaged in developing strategies to cope with what are viewed as very likely adverse consequences of significant climate change, with some of these on the near-term horizon of the next decade. First, and most visibly, there have been international and national laws stemming from the Kyoto protocol to motivate companies in the energy sector (electric power, oil and gas) and in allied energy-intensive industries (steel, pulp & paper, glass, aluminum, transportation and cement) to reduce emissions of GHGs (see Mansanet-Bataller and Pardo, 2008). Second, and near and dear to the hearts of the insurance industry, is the increased use of modeling by regulators and insurers to measure and price insurance coverage of catastrophe risks, for companies, households and public infrastructure. Third, are growing initiatives related to adaptation strategies (Linnerooth-Bayer et al., 2009; Munasinghe, 2009), which are focused on coupling project development activity to combat the damages of climate change with insurance and risk management services. Among the very visible signs of the carbon economy is the wave of new laws and regulatory incentives associated with renewable energy. For example, the Climate Change Package approved by the European Union in April 2009 will have immense implications for how energy-intensive businesses function in Europe. It will affect everything from plant location decisions to technology choices, and ultimately the profitability and risk, of these industries.

The insurance industry has begun to address the increased risks involved with climate change (see Mills, 2009). Major position statements and research reports have been issued by the World

Economic Forum (WEF, 2008) and the Geneva Association (2009). Munich Re and Swiss Re have been in the forefront in promoting research on the effects of climate change, with Asian insurers like Tokyo Marine Group joining forces to develop new assessment tools and weather-related risk products to market. The effects of climate change are expected to include in the near term potential increases in flooding and surge damage, increased tropical cyclone activity, and increased impacts of droughts and temperature rise on agriculture and water supply. Going out another decade or so, we could reach critical tipping points related to climate change, potentially large migrations from countries at or below sea level to other less affected regions, a possible flip in climate in Northern Europe if the Gulf Stream shuts down, large and uncertain impacts from decreases in biodiversity in plant and animal populations—in other words the potential changes could be huge.

Against this turbulent background of new risks unleashed by climate change, the insurance industry faces some important challenges in defining its proper role, in convincing external stakeholders, including political decision makers, of the legitimacy of this role, and in developing and marketing the needed products and services to play its role effectively. Many of the catastrophe risks attributed to climate change are not new per se to the insurance industry. Certainly the general issue of catastrophe cover for large correlated risks, be they from tropical cyclones, earthquakes or terrorism, is now well understood. Indeed, special designation of some weather-related risks as climate change risks has its own perils, as a common approach to catastrophe risks should be based on the character of the underlying hazard, and correlations across insured losses affected by this hazard, and not what the hazard is called. Nonetheless, I believe there is a real opportunity, and a real urgency, in the current growing awareness of the threat of climate change, to address weather-related catastrophe risks under the heading of climate change.

The paper proceeds as follows. In the next section, I consider the threats arising from climate change for the economy as a whole and for the insurance industry. I then focus on the special features of climate change that make it difficult for policy makers and normal citizens to cope with its potential consequences, and to the central role of science and scientists in legitimating insurance and risk management activities related to climate change. Two areas of current interest are discussed in light of this commentary: 1) the product side of traditional insurance and reinsurance and how science and risk finance can contribute to more resilient risk bearing structures in the climate change area; and 2) the special case of financing adaptation policies in emerging economies where insurance penetration is low, and where special problems exist in signaling risk exposures using the normal insurance instruments. My concluding remarks summarize some of the opportunities and challenges I see for the insurance industry in the climate change area.

Implications of Climate Change for Insurance

The Nature and Scope of Climate Change

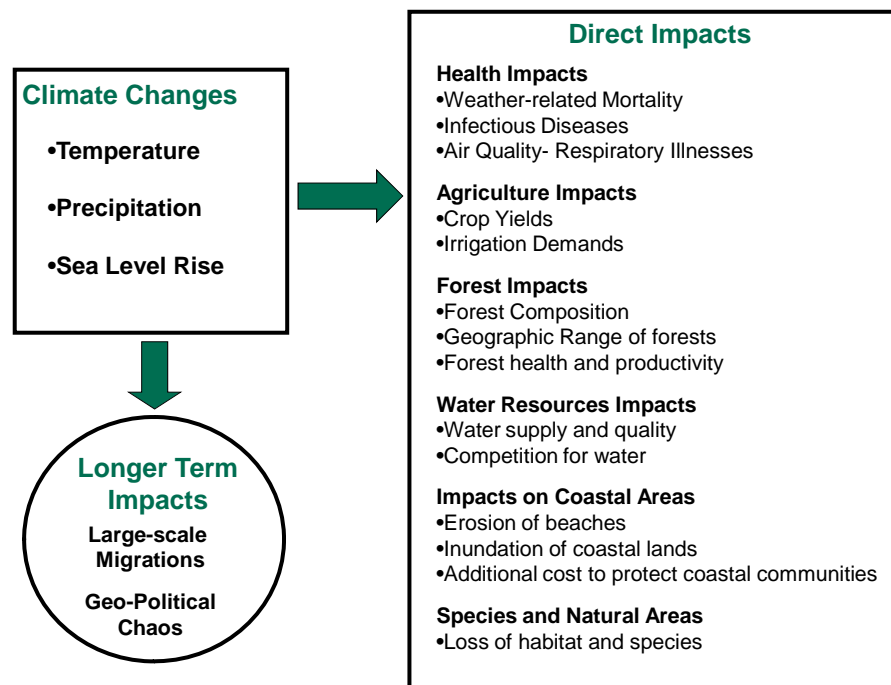
As explained in Munasinghe (2009), the 4th Assessment of the Intergovernmental Panel on Climate Change (IPCC), issued in 2007, was unequivocal in its finding that total radiative forcing of the climate now is unprecedented when judged against the evidence of global temperatures during the past several thousand years, and is due to rising concentrations of Greenhouse Gases or GHGs (CO₂, CH₄ & NO₂). Moreover, it is very likely human activities since the 18th century that have caused net warming of the Earth's climate, dominating over the last 50 years. According to the IPCC, more temperature and sea level rise seems inevitable, even with existing GHG concentrations. Although this is the "consensus opinion" of the IPCC and its many scientific and technical working groups, the uncertainty bounds on the magnitude of sea level rise and other effects are very large, and there are many scientific links in the chain of reasoning leading to these effects that are still in dispute. For example, based on very large simulation models of the earth's climate, the predicted rise in sea level in this century is between 20 and 60 centimeters with a median prediction of 40 centimeters if ppm concentrations of GHGs can be limited to 450 ppm (which will take vigorous and immediate actions to achieve). The difference between 20 and 60 centimeters is obviously very large in itself. When one couples this with the uncertainties in the carbon cycle and our general lack of knowledge about the causal features leading to climate change, there is plenty of room for skeptics to argue that we do not understand enough about this to know a) what to do and b) when to start doing it. Nonetheless, based on the imperfect evidence available, appeals to the precautionary principle, to the sustainability paradigm and intergenerational equity and to other notions of prudence have led to a flurry of activity in the past decade in attempting to respond to the threat of climate change. This includes, foremost, efforts to mitigate GHG emissions through the Kyoto Protocol and its associated implementing laws and regulations around the world, as well as international concern about the financing of mitigation and adaptation measures.

Figure 2 shows some of the predicted consequences of climate change based on the findings of the IPCC's 4th Assessment. These are effects at the median scenario associated with achieving significant reductions in GHGs by 2050. There are also beneficial effects, for some regions, with increased agricultural output in some mid-level latitude regions, and increased forestry yields. However, most of the news is bad, and especially for the developing world. The main negative consequences expected are based on predictions of higher maximum temperatures and heat waves over nearly all land areas, higher minimum temperatures and fewer cold spells over nearly all land areas; more intense precipitation events over many areas; increased summer drying over most mid-

latitude continental interiors and associated risks of drought and wildfires; and increased tropical cyclone mean and peak wind intensity.

The Role of Insurance

Insurance can and should play a key role in signaling to households and businesses the magnitude of the risks they face from natural hazards and what they can do to mitigate the consequences. In economies with well-developed insurance markets⁴, this signaling is best accomplished through risk-based insurance rates, supported by reliable information provided to property owners, financial intermediaries and communities. Major studies such as Kunreuther and Michel-Kerjan (2009) have verified the role of insurance as a fundamental policy instrument in providing information before the fact on the value of mitigation and after the fact in providing cash injections to aid in recovery.



Based on Munasinghe (2009)

Figure 2. Predicted consequences of climate change through 2100

⁴ I discuss below the special case of emerging economies where insurance penetration is low and where alternative means need to be pursued to provide signals on risks faced and incentives for cost-effective mitigation.

In theory, appropriate geographical diversification and risk-based pricing should allow the insurance and reinsurance industry to cope with even large changes in frequency or severity of events. Barring sudden tipping point phenomena (see Kousky et al, 2009), the likely appearance of climate change effects will be more gradual and over sufficiently long time spans, say 5-year periods, for insurance to adjust policy conditions and reinsurance treaties to track changes in the overall exceedance probability curves. If this assumption is true, then the central problem for traditional insurance markets is whether this process of necessary adaptation will be acceptable in the market, and whether regulators and legislators will work in partnership with the insurance industry on these problems and allow rates to be adjusted appropriately as new information becomes available. Besides solvency and price regulation that are subject to strong regulatory controls in many jurisdictions, other governmental actions will also strongly affect the ultimate magnitude of economic value at risk from climate change, including: providing information on risks, data gathering on storm activities and asset locations, zoning, building regulations and strengthening of public infrastructure. Moreover, the government also plays a central role in establishing and reinforcing the cultural pre-conditions of personal responsibility for locating assets in vulnerable areas, and in gaining agreement on the “social risk contract” regarding the structure of risk-bearing for climate change events borne by the government and by individuals. In the best of all possible worlds, the latter arrangements (the terms of governmental participation in risk bearing) will be determined in advance.

Thus far, the results of climate change on insured losses are not that clear, but this could change quickly in the future. Miller et al. (2008) considered loss data from weather-related disasters since 1970, and normalized these data to remove the effects of demographics and the increase in the economic value of assets in vulnerable areas. Their results show a 2% upward trend in economic losses from weather-related disasters since 1970. However, this result is sensitive to the currency base used for loss evaluations and to various other idiosyncratic features of the post-1970 period—e.g. leaving out the effects of Hurricane Katrina significantly affects results. The authors conclude that while there is “limited statistical evidence of an upward trend in normalized losses from 1970 through 2005”, there is “insufficient evidence to claim a firm link between global warming and disaster losses.” (Miller et al., p.240) Knutson (2008) draws a similar conclusion in his summary of the conflicting scientific evidence concerning the relationship between climate change and tropical cyclone activity. He concludes, however, that while it is too early to determine if climate change or greenhouse gases have affected intensity or frequency of storms to date, it is nonetheless likely that increasing concentrations of greenhouse gases will in the coming century cause hurricanes to be more intense, with associated increases in rainfall, floods and surge damage in coastal areas. Fact sheets and studies from the major reinsurers support this view (e.g., Heck et al., 2006; Munich Re, 2009; Swiss Re/ProClim, 2009). Moreover, recent results on melting of the icecap in Greenland are

disquieting on the speed of expected global sea level rise (van den Broeke et al., 2009). Given the increased property and populations at risk on the coast lines in economically important regions in the Americas, Asia and Oceania, all of this points to a major threat to global economic activity and a major challenge for the insurance industry.

Science and Risk Finance as Essential Pillars of Catastrophe Insurance

Science and Scientists

Science is generally understood as the evolving set of claims, and the methods and evidentiary backing underlying these claims, pertaining to particular phenomena of interest in the world. I will not revisit here the on-going debate between Kuhn and Popper on subjectivism vs. objectivism and whether the evolution in science occurs via paradigms or in piecewise evolutionary stages of corroboration and falsification.⁵ Whatever one's views are on this debate, it is nonetheless unobjectionable to note that science is practiced by scientists who themselves may disagree about the current state of knowledge in their area of expertise. To know what science is and what it holds to be true at any moment of time, it is therefore necessary to consult scientists themselves. This naturally gives rise to a hierarchy of technocrats and scientific power structures vying for visibility and hegemony in determining which competing claims are the best reflection of current knowledge, and which scientists should be considered the leading spokespersons for particular areas of science.⁶ Interpreting the often discordant voices that arise in the on-going evolution of science thus requires judgment and time. In the process, the natural separation between those with credentials to make credible scientific claims in a particular area and decision makers and stakeholders who have interests that depend on the nature of these claims gives rise to obvious tensions in trying to get to the bottom of what scientists are really saying. It is also rather frustrating for policy makers and private decision makers who are put in the awkward position of trying to defend their decisions on the basis of one or another scientific claim, when they lack the expertise to make judgments themselves about competing scientific claims and when scientists are unable or unwilling to come to agreement on sufficiently precise predictions to support or reject clearly some course of action.

⁵ See Kuhn (1993) and Popper (2002). For a brilliant account and synthesis of the issues involved in this debate see Bernstein (1983).

⁶ For a discussion of the social structures connecting scientists, and their relationship to policy, see Beck (1992) and Jasonoff (2004).

This tug of war among competing theories and qualifications of theories is particularly evident in the area of climate change. Here scientists of various stripes have attempted to provide a consensual opinion in the IPCC assessments as to the “facts” (e.g., what has been the evolution of the average global surface temperature), the causal mechanisms at work (the greenhouse effect and the carbon cycle), and the relationship of these to human activity. It is quite natural that the result has been complicated and attempting to arrive at a consensus statement across climate scientists very difficult. For example, the IPCC wrestled for years with the words “likely”, “probable”, “very likely” and so forth attached to the prediction that climate change was the result of human activity and that this required a commitment globally to reducing GHG emissions. I will explore later some of the consequences of this verbal wrestling in the scientific community for the on-going public debate about climate change and risk reduction activities related to it. For the moment, I wish to explore more directly the consequences of lack of knowledge for a decision maker facing a given risk. In the process I hope to clarify some important interdependencies between scientific knowledge and decision making under risk.

Epistemic and Aleatory Risk

Climate change and other catastrophe risks pose an interesting mix of risk and uncertainty and it is important to distinguish these carefully. An important distinction began to be made in the very early days of catastrophe modeling between epistemic risks and aleatory risks underlying the derivation of exceedance probability curves in support of insurance underwriting and pricing.⁷ Epistemic risks are those that arise from our lack of knowledge about a particular phenomenon and are usually captured under the heading of “model risk”, while aleatory risks are the result of natural and irreducible randomness inherent in natural phenomena. The standard approach to multiple competing models of reality has been robustness or sensitivity analysis (to the extent that the competing models can be characterized by parametric variations of some meta-model). The original theory for addressing this problem as a choice problem was “second-order probability theory” in which (in the spirit of the pioneering work of Leonard Savage) each possible model was viewed as a competing state of the world. By assigning subjective likelihoods that each of these models was the true model, one could generate a two-stage problem, with the first stage reflecting the probability of each model being the true model and the second stage reflecting the consequences of various choices given each particular model. The resulting generalized choice problem would then involve both the decision

⁷ So as not to overburden the reader with references to this very interesting history, I refer here only to the recent summaries, In the case of catastrophe risk and insurance, the best recent summary of “uncertainty analysis” is Grossi and Kunreuther (2005).

maker's knowledge about the validity of various models and the consequences (both upside and downside) of choices under various models.

Later writings on uncertainty analysis in the catastrophe risk area recognize two basic types of risk associated with this general scenario: epistemic risk and aleatory risk. Epistemic risk (from the Greek word "episteme" meaning "knowledge") arises from our lack of knowledge about the appropriate model or theory that might be valid or relevant for a particular phenomena, and aleatory risk (from the Latin root "aleator" for dice player) arises from randomness inherent in a phenomena (though this randomness itself may be defined or qualified by the underlying epistemic assumptions made).⁸ While there is a gray area in defining epistemic and aleatory risk, the key difference is that epistemic risk can be reduced through exploration and knowledge acquisition, better theory and better data, whereas aleatory risk cannot be reduced by such scientific activities. This fundamental difference has given rise to a number of related approaches to decision making under uncertainty, based on the value of information and model-based estimation issues such as those advanced in extreme value theory. Let us briefly explore here the implications of epistemic and aleatory risk for catastrophe risks by considering two general applications.

Insurance and Mitigation Decisions for an at-risk Private Party under Ambiguity

Consider a homeowner or business that is concerned with catastrophe risk. The focal decision maker might consider options such as insurance or mitigation before the fact in order to either reduce or pay for losses resulting from an event. In the Appendix, I use recent results on ambiguity theory due to Klibanoff et al. (2005) to formulate a simple (two-period) version of this problem for a "rational" economic agent, i.e. an agent whose preferences for risk and for uncertainty satisfy a set of axioms that are intended to capture rational choice⁹. The structure of this problem and its solution are roughly as follows (see Figure 3 for a flow diagram).

Problem: Determine ex ante investments in mitigation and insurance as well as in acquisition of knowledge to reduce epistemic uncertainty so as to maximize the total

⁸ For example, as described in Grossi and Kunreuther (2005), in predicting the consequences of earthquakes, recurrence rates for seismic activity, for propagation of seismic energy and for geological conditions, and the contents and fragility of buildings all represent epistemic assumptions that are necessary for modeling insurance losses from seismic activity in a particular region. In addition to these sources of epistemic uncertainty, there is a natural randomness associated with the effects of such earthquakes. Such randomness would remain unresolved even if one knew for a fact when and where earthquakes would occur, the complete geology of a particular region and all relevant details of affected buildings.

⁹ See Kleindorfer et al. (1993) for an introduction to various theories intended to capture rational choice.

expected utility of the residual risk, given a specification of aleatory risk that is conditional on the level of the decision maker's knowledge, and given bounds (beliefs) of the decision maker on the magnitude of his epistemic risk.

Solution: The solution trades off the expected benefits and costs of loss reduction and insurance coverage. However, the solution also accounts for the cost of reducing the epistemic uncertainty by investments in better data and better knowledge and the benefits of potential increases in precision of underlying knowledge in reducing risks and in better choices of mitigation and insurance coverage.

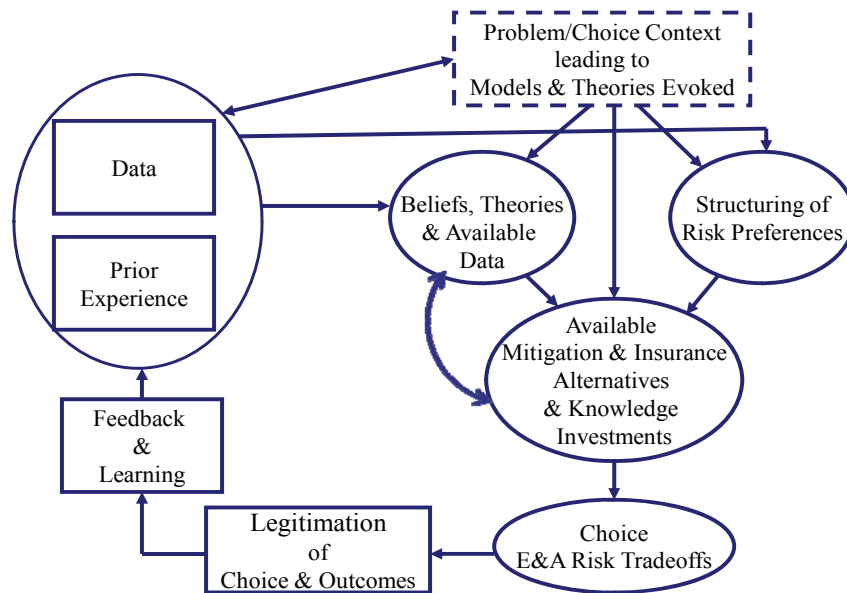


Figure 3: Epistemic (E) and Aleatory (A) Risks in Choice under Uncertainty

The logic captured in Figure 3 is that rational choice involves both investments in better knowledge as well as in risk reduction, given the knowledge one has attained. This is surely a rather trite assertion for any sophisticated risk management group. What is more interesting is that epistemic (or knowledge-based) risk and aleatory (i.e. randomness) risk are tightly intertwined with choice. It is the interaction of both with choice alternatives that co-determines for a given individual or business the optimal tradeoffs between investments in data and knowledge and investments in mitigation and insurance. (The issue of legitimation of choices ex post will be discussed further below.) From the perspective of providers of risk management services, this should be good news in terms of sales of

assessment, prevention and mitigation services. It underlines the importance of knowledge acquisition, not just as an end in itself, but as a fundamental input to rational choice.

Setting Economic Reserve Capital for an Insurer/Reinsurer

The underlying science of climate change will have direct effects on insurer's underwriting and reserve decisions, as both of these are directly related to the insurer's exceedance probability (the insurer's EP curve) and expected profits. The logic here is clear enough to anyone who has dealt with catastrophe models, but a few of the details of this are nonetheless worth noting. The model in the Appendix frames the analysis of optimal reserves in terms of a solvency-constrained, expected profit maximization model for a specific insurer (the model dates from Stone (1973), as elaborated in Kleindorfer and Klein (2003)). The model captures several tradeoffs. The level of the solvency constraint itself reflects the insurer's appetite for risk and, in particular, the tradeoff between the costs of increased surplus and the franchise value of the firm going forward, which is put at risk under insolvency. For any specific target level of insolvency probability, maximizing expected returns from a given equity base implies that the insurer will attempt to market its risk coverage to a geographically diversified portfolio of risks. On the other hand, scale economies in marketing, distribution and claims processing may drive the company to market more intensively in some areas than in others, leading to increased (positive) correlation among the risks in the insurer's portfolio. This tradeoff embodies the interaction of demand and marketing payoffs relative to the costs of the capital required to support the book of business chosen by the insurer.¹⁰

My immediate interest in this model here is to note the consequences of large uncertainties on the determination of the EP curve of the insurer. Figure 4 below shows, for a given underwriting portfolio, such an EP curve, with uncertainty bounds associated with this curve. The mean EP curve is the solid line and the dashed lines represent lower and upper bounds on the mean EP curve corresponding 5% and 95% confidence levels. I discuss below the sources of these uncertainty bounds. For the moment, they can be thought of as resulting from epistemic risks associated with the data and models used to develop the EP curve.

¹⁰ These tradeoffs are further complicated if regulators contravene adequate rates or cause cross-subsidies through rate compression. In this sense, the stakes of getting the science underlying catastrophe insurance right involve not just the insurer, but also the regulator. For a discussion of regulatory issues related to the catastrophe risk area, see Grace et al. (2004).

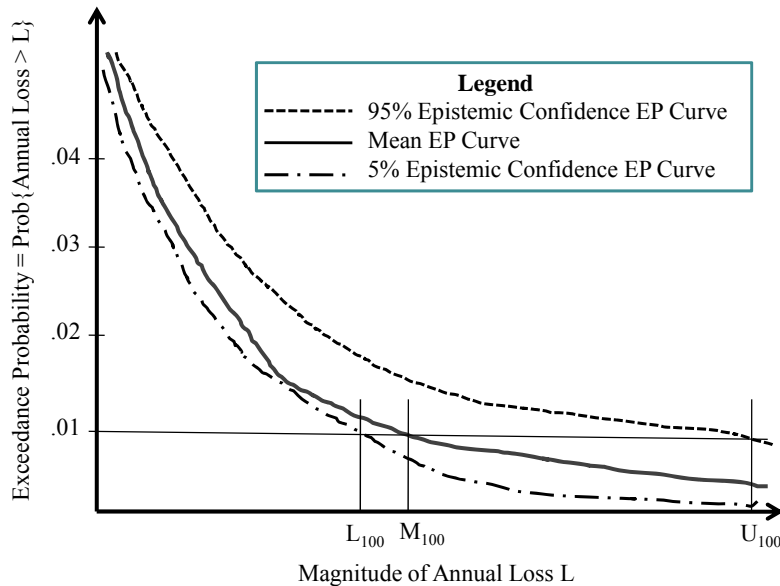


Figure 4: Illustrating Reserving Decisions under Epistemic Uncertainty

While Figure 4 is purely speculative (a free-hand drawing by the author), it illustrates an important point. When uncertainty is low, and the 5% and 95% epistemic confidence bounds are close to the mean EP curve, there is little tension in concluding, as many insurers and reinsurers do, that the mean EP curve is what should be used to determine capital requirements (which come from premium income, reinsurance, securitization instruments and enterprise capital) to assure solvency. However, under conditions of extreme uncertainty, there is increased tension between the notions of epistemic and aleatory risk and it is quite possible that an insurer would have a different appetite for aleatory than for epistemic risks.

What might be the sources of such epistemic risks in weather-related events and why might they be greater in an era of climate change? The answer lies in the uncertainties associated with the science of climate change. Catastrophe modeling companies have always had to grapple with the epistemic risks associated with incomplete or inaccurate data on vulnerable structures, with uncertain fragility curves and with the frequency and severity of storms in any given future period. What is changing under climate change is the nature of the hazard itself, including both tipping point effects, non-linear changes in damages and the general question of whether storm activity itself is on the increase because of global warming. While the historical evidence cited above on observable trends in tropical storm activity is not yet of the quality to suggest major increases in epistemic bounds, the language of climate scientists these days is certainly in the

direction of hockey-stick and tipping points in weather patterns related to climate change.¹¹ If this is a proper interpretation, then one may well expect greater uncertainties to be reflected in the results of catastrophe modeling firms going forward, with the noted tensions for both insurers and their regulators in determining capital adequacy requirements. The only known cure to lessen these tensions arising from ignorance and epistemic uncertainty is research and knowledge acquisition. This brings us four square back to the fundamental role of science in providing a credible foundation for codifying and reducing epistemic risk.

Legitimation and Science in Support of Catastrophe Risk

Legitimation in the Decision Sciences

Legitimation theory in its modern form derives from the German philosopher Jürgen Habermas (1973). A short summary of the descriptive theory of legitimation could be stated as follows (Kleindorfer, 2009b): if a decision maker knows s/he is being observed while making a decision, this will have predictable effects on the process and outcomes of decision making. The parallel prescriptive theory of legitimation supports the notion that it is both sensible and desirable to subject some aspects of decision making to *ex post* review, both to justify the process and outcomes of choice and to provide affected stakeholders with assurance that their interests have been considered. Legitimacy of institutions is central in an open society, both for accountability of these institutions as well as to attempt to improve regulation (e.g., in terms of efficiency or fairness).

This line of thinking has been subject to experimental and empirical work over the years. For example, Simonson and Nye (1992) designed several studies to determine whether accountability (‘anticipation of required justification’) would affect decision making, and they found this to be so. Their studies also show that decision biases may not be reduced by accountability alone, because it is not performance that subjects seek under conditions of accountability but rather the favorable opinion of those able to observe and/or sanction their behavior. The extensive antecedent work of Cottrell (1968) underscores the findings that anticipation of evaluation has rather different effects on behavior than passive observability per se.

With an eye on the large uncertainties associated with climate change, experimental results on the effects of ambiguity on legitimation are relevant to our discussion. Similar to the model of the

¹¹ See the discussion in van den Kousky et al. (2009) for a review of possible tipping point effects that might produce losses well above historical levels.

Appendix, these experiments considered situations in which the probabilistic processes underlying uncertain outcomes were only known approximately by the decision maker. This matter was first examined by Curley, Yates and Abrams (1986). They examined experimentally differences in individual choice under conditions of risk (known probabilities of outcomes) as contrasted with conditions of ambiguity (vague probabilities of outcomes). They added the additional aspect to their experiment that the choices made by individuals were played out either in private or observed by a group. When a group could observe the results of an individual subject's playing of ambiguous choices, and this was known in advance, subjects were prepared to pay significantly more to avoid having to play lotteries with ambiguous outcomes. One explanation for this, based on legitimation theory, is that when individuals anticipate the need to be able to explain (or even expose) to others their choices, ambiguity of outcomes becomes even more undesirable than it is in isolated personal choice settings. The reason is apparently the difficulty in explaining one's own decision processes in a convincing manner to others when ambiguity is a significant element of a decision context.

The psychological and behavior decision making literature on choices under ambiguity and uncertainty has considered several other important issues that bear on the knowledge underpinnings of choice under uncertainty. I will just note a few of these.¹² First, individuals tend generally to be overconfident and myopic and this overconfidence is, if anything, exacerbated when expertise and judgment are required (see Heath and Tversky, 1993). The impacts of such overconfidence (“it won't happen to me”) and myopia (“the benefits of mitigation several years out are not relevant to my current choice”) have significant impacts on individual choices related to mitigation and insurance in natural hazards (e.g., Kunreuther and Michel-Kerjan, 2009). Second, there is considerable inertia in mental models (one explanation for which being the cognitive energy it takes to re-integrate a new mental model with existing beliefs). The result is that, rather than adopting a posture of balancing supporting and rebuttal evidence on the validity of one's current mental model, there is rather a search for confirmatory evidence that one's current model is the right way to go. As Taleb (2007) has pointed out in his writings on “black swan effects”, this results in far too many hundred year events occurring every 5 years, giving rise to cries of “oops” and “duh”, but rarely to an adjustment of our mental models (e.g. mental models based on Gaussian theory). Third, there are herd dynamics and contagion effects evident in the use of models. Some of these are understandable in terms of minimizing coordination costs of social coordination (a point underscored by Schelling (1978) and Beck (1992)), but the result is in many cases the adoption of models based on general acceptance rather than on the basis of the latest science. Finally, there appears to be a mix of the rational and irrational when it comes to dealing with severe uncertainty. Part of this arises undoubtedly from our

¹² The literature on these matters is discussed in detail in Kleindorfer et al. (1993).

biological heritage in seeking meaning and order in life so that we can continue to function without undue neurosis. And certainly, the mere thought of making choices of consequence under conditions of ambiguity and ignorance calls out for company.¹³

This research from the decision sciences suggests that observability of behavior, together with expected valuation and defined norms, act together to alter reasoning processes and decision outcomes in ways that align process and outcomes with accepted norms of making such choices. While this may be intuitively obvious, it has immense implications for the climate change area, and for science in support of decision making related to this.

Climate Change and Legitimation

The basic problem with assuring reasonable and reasoned outcomes in the area of catastrophe risk management and climate change is the lack of an agreed framework and principles (or norms if the reader prefers that term) for judging what is a good process and outcome. This is true for nearly any group of stakeholders one wishes to consider in this debate. The recent exchange of views among economists triggered by the Stern Report (see Stern, 2008 for some of the arguments) suggests some of the recognized characteristics of the problems associated with this issue. These include huge uncertainty, large time lags between actions and effects, and massive complexities and knowledge gaps in the underlying science. For legitimation, these characteristics imply heavy weather for both validation of policy actions, as well as individual choice related to mitigation and insurance.

Aggregate valuation of alternative options: As the problems here are long term in nature, and beyond the temporal reach of market-based instruments, political choices are fundamental in determining policies. The lack of a clear market-based definition of efficiency in political choices gives rise to any number of problems in arguing for an appropriate course of action. Notwithstanding the predilection of economists, it is not helpful to insist to the public or to regulators and legislators, as surrogates of the public, that the only principles that matter are economic principles. This is even truer in the international arena where calls to the developing world to commit to GHG reduction targets have by and large been met with a cold shoulder, an issue to which I return below. The Stern Report itself concludes that economic principles alone do not suffice to come to a conclusion about what to do concerning climate change. Rather, one needs to apply additional principles from the realm of ethics to make the case for immediate costly mitigation borne by current generations in the developed

¹³ The increased need for traveling companions in uncertain times may be understood as the result of the existential need for reinforcement and endorsement of our worth as individuals, where this comes primarily through our interaction with others, per the trenchant philosophical writings of Soren Kierkegaard and Martin Buber.

world versus more gradual approaches which may shift the burden of losses and impacts to developing countries and future generations.

Individual valuation of alternative options: In participating in the social processes underlying political choices, or in the international political arena, how should the views of citizens be shaped, informed and represented in the political process? In terms of representing values and preferences of citizens in the political process, survey methods such as contingent valuation are likely to be of limited use because of the characteristics (uncertainty, complexity and intertemporal) of the climate change problem (Fischhoff, 1991). How to shape, inform and represent individual preferences about approaches to climate change, and the role of advanced preparation including insurance, remains a largely open question in valuing and legitimating alternative approaches.

International and intergenerational equity, irreversibility and intertemporal choice: Legitimation problems are particularly difficult in this context because it is impossible to consult all the affected parties at the time policy choices are made. This is especially salient in the problem of developing vs. developed countries and the problem of determining equitable burden sharing. The special problems of intergenerational equity and irreversibility have been at the heart of the climate change debate, just as they were for radioactive waste (Easterling & Kunreuther, 1995). More generally, the “precautionary principle” and the whole sustainability debate itself has been focused on the central question of what it actually means for present generations to live in such a manner so as not to disadvantage future generations. Coupled with great uncertainty, irreversibility of some damages and very long time frames for effects, these characteristics together bring climate change to the very limits of what human decision makers are able to cope with in terms of models of rational choice (Brekke and Johansson-Stenman, 2008; Kleindorfer, 2009a). The result is an unsettling cloud of normative uncertainty as to who should be responsible for the costs of GHG mitigation or for realized losses from catastrophe events that may be related to climate change.

Low-probability, High-consequence events: Added to the above are the continuing perplexities of risk management and mitigation associated with the low-probability, very high-consequence outcomes of climate change. Howard Kunreuther’s contributions over the years have highlighted the huge difficulty that human decision makers have in coming to grips with these problems. The lack of easily interpretable feedback on climate change policies contributes to the ease of misinterpretation and denial of the noisy signals that arise from climate change and to the ability of third parties to obfuscate matters in their interest. Results in the climate change arena need to be interpreted by panels of scientists, run through complicated models and qualified in ways that make the results nearly incomprehensible to all but a limited number of affected parties. In this context,

individual choices, e.g. about location or retrofitting of homes, are prone to basic biases of threshold decision making and myopia (see Part III of Kunreuther and Michel-Kerjan, 2009). By extension, public reactions to zoning and other community or societal mitigation practices are often muted, distorted or confused.

What guidance can research on legitimation theory provide us in our discussion of the role of science in helping to cope with the risks of climate change? According to Habermas, we should engage in open discourse and attempt to promote communicative rationality, rather than holing up in our disciplines and attempting to legitimate the goodness of one or another policy or model by decorating our ideas with the plumage of intellectual certifications or professional consensus within the industry. This would call for a proactive approach by the industry to engage both the general public and country risk planners, and their regulatory surrogates, as articulated, for example, in the conclusions to the Report on Climate Change by the Geneva Association (2009). At first glance, Habermas' call for a more democratic approach would appear to be an impossible recipe to follow, given the complexities and international scope of this problem. However, on reflection, are the ideas so difficult that individual citizens and non-insurance experts and policy makers cannot be brought into the discussion? Can they not be made aware of the stakes in meaningful terms? Of the trade-offs for themselves and their grandchildren? Rather than speaking in terms of \$800 billion of NPV of the global GDP versus \$4 trillion (the types of economic numbers attached to the Stern report for various alternatives), could not the consequences of alternatives be expressed in terms that are meaningful to an individual in various parts of the world? I think the answer to these questions is most definitely yes. Moreover, given the magnitude of the stakes in this problem, it seems to me critical to bring in the citizens of the planet into a more meaningful and urgent debate of these policies, which have the potential to significantly affect their lives and those of many generations to come.

An active role for science and scientists will be important on at least three levels: i) science for risk managers and business leaders; ii) science for individual citizens; and iii) science for policy makers. Given the level of the potential losses from climate change, there is already a deep and contentious debate, which is engaging business leaders, citizens and policy makers. In some countries, this has been a very public debate¹⁴, while in others the debate has become a largely political issue. In the USA, for example, major business newspapers and corporate blogs continue to give large play to the possibility that the “whole climate change” debate may be nothing but a hoax

¹⁴ France and Germany are good examples of this, with major newspapers in both countries (e.g., *Le Monde* in France and *Frankfurter Allgemeine Zeitung* in Germany) featuring on-going special sections on “the planet” and with governmental ministries dedicated to sustainable development focused directly on climate change issues.

foisted on the public by ill-informed left-wing individuals with nefarious central planning tendencies who wish to impose the will of the government on otherwise efficiently functioning market activities.¹⁵ Rather than focusing on the very real uncertainties in the progress of scientific explanation on the timing and magnitude of climate change, much of the discussion has focused on short-term costs for business of carbon mitigation and on the uncertainties and holes in the science of climate change. The obvious consequence of this is to erode the political will of many legislators to support public policies to address domestic policies on climate change, let alone policies that require subsidies of other countries, e.g. the solidarity fund for adaptation projects in developing countries. It is easier to dismiss such efforts as anti-market forces and bureaucratically inspired growth in government than to see these as responses to real threats.

There is, of course, no easy answer to how science should be involved in providing a more reasoned fabric to underpin public debate and policies. The history of science, per Kuhn and Popper, shows that the natural evolution of complex domains like climate science will come in fits and starts, with evidence and knowledge accumulation occurring over decades and longer. Asking scientists to compress complex interactions into simpler and more understandable terms for laymen is also no remedy for what is after all a complex matter. Leaving the interpretation to third parties and the media also has many problems. In the end, the apparently clumsy process of technical working groups and the normal research, review and publication process and continuing efforts by both private and public agencies to interpret the state of science of climate change is probably as good as we can do. It is important, however, to continue to measure public knowledge and attitudes toward climate change science and policies in order to understand their conceptions, misconceptions and concerns. If we have learned anything from the science of risk communication over the past 40 years, it is that experts and lay individuals very frequently have different ways of perceiving and coming to terms with complex risks (Slovic, 1987). Without some degree of sophistication on the basic science of climate change by citizens, there are real dangers that public policy initiatives to cope with climate change will be undermined by ignorance and self-serving elected officials pandering to such ignorance.

The implications for industry and risk management of improved knowledge of climate change risks are also important. Whether in developing or developed economies, there is a vast difference

¹⁵ For example, in the editorial column "Potomac Watch" published in the *Wall Street Journal* on November 26, 2009, after the compromising emails of the Climate Research Unit of East Anglia University were published on the Internet, columnist Kim Strassel notes that: "... if this Democratic Washington has demonstrated anything, it's that ideology often trumps common sense. Egged on by the left, dug in to their position, Democrats might plow ahead. They'd be better off acknowledging that the only 'consensus' right now is that the world needs to start over on climate 'science'."

between sophisticated and ignorant clients of insurance and risk management services. A sophisticated client knows that there are significant uncertainties surrounding the underlying science and engineering quantification of risk and that insurers and capital providers are likely to respond to this in providing risk transfer products that are priced to reflect the underlying uncertainties. The sophisticated client also understands that mitigation is a necessary ingredient to reduce risk and the expected losses from these risks. An ignorant client, on the other hand, may be frozen by dread into a sense of inaction or, in the spirit of cognitive dissonance, may act as if the risks involved are actually minimal and the insurance instruments offered are merely taxation in disguise, with no relevance to their lives or their actions. The insurance industry clearly has an extremely important stake in increasing the sophistication of public and private parties who will be affected by climate change. In my view, they can best do this, working with others, by promoting objective research that will provide a balanced perspective on what is known and not known about climate change and what the implications of our evolving state of knowledge are for cost-effective mitigation and for the pricing of risk transfer products to cope with the impacts of climate change. As Hiroyuki Hata (2009) notes in his recent summary of insurance industry responses to the climate change debate, this process of engagement has definitely begun. A central question here is what principles might be put forward to position the insurance industry's response to climate change and to improve the perceived legitimacy of the industry in responding to the challenges of climate change.

Principles underlying Catastrophe Risk Insurance under Climate Change

Several knowledgeable groups have articulated principles that are likely to be central to assuring the efficiency and efficacy of insurance in the climate change arena (WEF, 2008; Kleindorfer et al. 2008; Kunreuther and Michel-Kerjan, 2009; Geneva Association; 2009) and are also clearly in evidence in well-known reports on the economics of climate change by Stern (2007) and Garnaut (2008). As relates to insurance, these various position statements and research studies all agree on two basic propositions:

1. With respect to insurance, in particular, risk-based pricing based on sound science to quantify the risks is a central pillar of insurability and of sustainable approaches to catastrophe risks arising from climate change. This principle is important not only as a critical underpinning of insurance markets, but also in providing proper signals for households, small businesses and firms to adopt cost-effective mitigation choices and adaptation strategies related to climate change. It has immense implications for public-private partnerships for collecting reliable data and on acceptance of actuarial and model-based approaches to quantify catastrophe risks.

2. In matters that intersect with the economy, it is desirable to rely on markets to implement choices, even when the choices involved derive from ethical principles or are the outcomes of a political process. Generally, markets promote transparency and innovation. Reliance on markets allows those affected to adapt, flexibly and autonomously, to local conditions. This principle applies both to insurance as well as to the carbon economy and other elements of the economic response to climate change. They apply both to direct insurance instruments such as traditional business and homeowner policy coverage as well as to securitization instruments linked to capital markets.

Beyond the above two principles, several others are advanced in Kleindorfer et al. (2008) and Kunreuther and Michel-Kerjan (2009), including perceived fairness and affordability, which are critical determinants of acceptability of any approach to catastrophe risk. This means that the costs of mitigation measures and insurance should be commensurate with the means and abilities of individuals, companies and countries to undertake or pay them. If costs of insurance reflect risks, one might need to consider providing financial assistance to individuals in hazard-prone areas needing special treatment (e.g., low-income uninsured or inadequately insured residents and businesses). In emerging economies, as I will discuss below in greater detail, this effort will require financial support from the international community and international organizations. A further principle of great importance, given the problems of legitimation noted above, is the following.

3. Risk management and communication strategies should help inform the affected public of the risks they face and the available cost-effective mitigation and recovery options. Each country/national government should articulate a clear social contract identifying the expected behavior of their citizens and the role of the private and public sectors in reducing losses and in paying for the losses from natural and man-made disasters.

To date, catastrophe modeling and insurance pricing have focused resolutely on the short term. This reflects the general belief that policy terms of policies and contracts can be renegotiated annually or for catastrophe bonds in 2-3 years. As argued by Kunreuther (2009a), there is a need to expand the temporal reach of both modeling and policy terms to include multi-year arrangements. This would promote greater sensitivity to the intertemporal and growing hazards associated with climate change. It would also broaden the scope of awareness and effective mitigation to the multi-year horizon that is going to be essential to address the value of mitigation of the consequences of rising sea levels and increased storm activity associated with climate change. To the extent that frequency of natural hazard events is also affected by climate change, it is clear that modeling and

contracting for multi-event reinstatement reinsurance contracts and other multi-period aggregate loss coverage instruments will become more important for reinsurance pricing. Thus, and especially in respect to risks associated with climate change, to the above principles we should add:

4. The evolution over time of weather-related catastrophe risks, and the magnitude of such risks, should be assessed over periods of time (e.g. greater than 5 years) sufficient to allow responsive mitigation and adaptation. Directly connected to this principle is the need for precaution and foresight, given the large uncertainties still associated with the science of climate change. This is further underscored by the possibility of truly catastrophic events associated with tipping point phenomena under climate change (e.g., Kousky et al., 2009). Moreover, it is easier to gradually phase in the impact of expected changes than waiting for a signal disaster to indicate that they are upon us.

New Products and Services and New Clients in an Era of Climate Change

Perhaps the most salient difficulty in embracing the above principles is the ever present human trait of not wishing to face bad news, and the potential increase in losses from weather-related events under climate change is definitely bad news. What is to be done? The insurance industry and scientists concerned with global climate change must help those who face the problem to face it and cope with it. My basic suggestion is in the spirit of market-focused value creation, namely to approach the ultimate asset owner and decision maker facing these risks and to address the needs of these asset owners directly. The problems are, of course, rather different in developed and developing economies and I will consider the challenges of developing appropriate products and services for these two client groups separately. For developed economies, there are three principal groups of potential clients for insurance services: Homeowners and SMEs (small and medium sized enterprises) with single-location risks, larger businesses with regional or global scope, and governments. For emerging economies, there are two groups of countries, those in the mid-range of development (with GDP per capita in excess of, say, \$2,000) and the poor countries below this level at the bottom of the pyramid. In both cases, the major client for insurance and risk management services is the government, although there is a larger nexus of external providers of capital in the form of aid to poorer countries, and these providers also need to be brought into the discussion and convinced of the efficacy of services provided.

Products and Services for Clients in Developed Countries

For the developed world, where there is high penetration of cat coverage and excellent modeling capabilities in place for risk assessment (see, e.g. Clark, 2007), the stakes are two-fold. First are the potential increases in the magnitude and uncertainty of the changes induced by climate change, including (for the business sector) the interdependencies and network effects of these across multiple lines of business; and second is the regulatory and legislative inertia that may prevent insurers and reinsurers from adjusting their policies and rates to the changing environment. Concerning the first, failing to respond to these changes in a timely fashion could be fatal for both insurers and reinsurers. For the second, it will undoubtedly take a concerted effort to work effectively with regulatory, governmental and inter-governmental representatives to define evolving risk-bearing structures that make sense in individual country markets and globally. In terms of the very basic issue of the magnitude of increased risks from climate change, long-term estimates in Stern (2007), Garnaut (2008) and IMF (2008) suggest a range of scenarios from 2050 onwards that are expressed in % of GDP reduction relative to a no-climate-change scenario of 1 to 3%, but with much larger losses within the range of the possible (see Kousky et al., 2009). How quickly these changes will materialize is a major uncertainty and this uncertainty itself calls for adaptive institutions and an informed citizenry that is ready to respond to changing climatic conditions. Given this reality, the following would seem to be the major challenges and opportunities in developing and marketing sustainable insurance products for the three major client groups in the market.

Homeowners and SMEs with Single-location Risks

The central challenge for homeowners and small businesses is to engage in cost-effective mitigation for the buildings they own. It is especially important to have the right risk-based signals clearly perceived when assets are initially located (i.e., when a building is built or rebuilt). There are many results in the literature indicating how difficult it is to provide proper incentives to do this, primarily because of misperceptions of probability and myopia of property owners. A central new idea in this regard is the use of multi-year insurance policies tied to the property (not to the owner of the property). As analyzed in Kunreuther and Michel-Kerjan (2009), such multi-year insurance policies have the potential to provide signals that rise above the threshold levels for investments in loss reduction measures that would otherwise not be taken. The payoff from such investments could be very large indeed. For example, using catastrophe modelling, Kunreuther and Michel-Kerjan estimated that if current building codes were applied to all residential properties in Florida, the result would be a 61% reduction in damages (saving some \$51 billion in expected losses) from the currently estimated 100-year-return-period event. A longer term perspective, perhaps promoted by multi-year insurance policies, could help move asset owners from a stance of “it won’t happen to me” to “making my property ready for climate change will increase its long-term value and my own sense of security”.

A strong ancillary benefit of this approach is that it would also provide incentives for insurers and governmental authorities to take a multi-year perspective on estimating annual losses from weather-related events. Currently, modelling and attention spans are largely limited to one year out events. This is not enough to overcome myopia and to encourage a longer-term perspective on cost-effective adaptation and risk reduction measures.

Larger Businesses with Regional or Global Scope

Globalization, together with its technological underpinnings in new communication technologies, has fundamentally changed the level of interdependency of financial and market activities, with many more actors involved in these activities directly or indirectly, and in real time. Per the arguments in Kleindorfer (2009a) and Kunreuther (2009), this increased interdependency and speed of responses means that organizational decision making and action confront a considerably expanded set of states of the world conditioning outcomes. The resulting increase in complexity currently exceeds organizational abilities to incorporate these increased states into decisions at the time they are made. What can be done about this from a management perspective is suggested by the anthropomorphic metaphor of an explorer entering uncharted terrain. That individual would do well to prepare mentally for surprises, to be agile and unencumbered by heavy baggage, to have increased acuity and perhaps communication capabilities to home base, and in general to have developed the ability to react to unforeseen and unforeseeable exigencies as they arise. This anthropomorphic metaphor of the prepared, agile explorer is helpful in thinking how and why insurance must be a leading partner in responding to the threat of climate change.

What are the implications of this increase in global interdependency for our topic here? A further complexity, recognized in insurance circles, is the issue of multiple perils and their correlations. The issue of correlations across major categories of risk has been fundamental to the Enterprise Risk Management approach of the past decade, following stunning examples from the World Trade Center attacks of 9/11/01 of the problem of missed correlations across lines of business. While this is now a generally recognized issue in the insurance industry, climate change may exacerbate this matter further. Similar to the contagion effects we have witnessed in the current financial crisis, deep blows from increased storm activity to one part of the world in, say, a manufacturing region in China could have strong ripple effects around the world.¹⁶ The significant economic losses associated with the Chichi (Taiwan) earthquake of September 21, 1999 and the great Chengdu (Sichuan Province, China) earthquake of May 12, 2008 foreshadow the nature and

¹⁶ See Papadakis and Ziemba (2001) and Harrington and O'Connor (2009) for a discussion of the direct and indirect economic losses arising from these two events.

magnitude of systemic losses that could arise from climate change as a result of the current tightly coupled global economic order.

Governments

As I argued earlier, there is an increasing and unavoidable intertwining of the public and private sectors in weather-related insurance related to climate change. The reasons are several. First, for climate change, the public sector is going to own the far tail of the loss distribution in any case, given the magnitude of the potential risks and the problem of reserving for such large losses.¹⁷ In countries with private insurance involved in catastrophe cover (e.g., Australia, USA, and Germany), insurance regulation in terms of rates, underwriting and coverage restrictions as well as solvency represent direct governmental interventions in catastrophe insurance. In other countries (e.g., France, New Zealand, Turkey), the government or its direct agent is a primary risk-bearer for catastrophe risks (see CCS, 2008; von Ungern-Sternberg, 2004). Governments at various levels are also involved in building codes and zoning. Data gathering and warehousing is often a primary government responsibility. In short, the government has a direct hand in many of the issues that are central to catastrophe risks and, in particular, to those that may be exacerbated by climate change. They also have an indirect hand these risks through regulations and laws that will affect location and operating practices of energy-intensive sectors that interact strongly with the carbon economy. Naturally, then, the actions of regulators and legislators will have important consequences for risk management in this era of climate change. However, the nature of politics, together with the inherent complexities of climate change and catastrophe risk, have thus far led mostly to debate but not to resolution of appropriate national and regional approaches to catastrophe risk and climate change. This matter is undoubtedly further complicated by the diversity of country-specific approaches to managing and insuring catastrophe risks (CCS, 2008).

More than any other industry, insurance has developed the integrated framework of prevention, preparation and risk transfer to help individuals and businesses analyze major threats to

¹⁷ Some would argue that where private insurers bear the brunt of some weather-related risks (e.g., wind damage in the USA), the government is only minimally involved. This is hardly the case, as there are vague lines between flood and wind damage, with the former the responsibility of the Government in the USA. It also seems clear that failure of State-level guarantee funds would lead to rescue operations by the Federal Government. Moreover, disaster relief and direct and indirect tax revenue losses associated with mega-events imply additional liabilities for the Government bears from mega-events. For all these reasons, I refer to the often unspecified but nonetheless quite real liabilities faced by government for catastrophe losses ex post as implicit mutualization. A basic argument I am making here is that this mutualization should become more explicit.

their well being, where possible avoid those that are too large to survive, mitigate others to an acceptable level and provide the resources in advance to recover from events. This framework and the principles articulated above must be the starting point for coping with climate change risks. Most importantly, working with regulators, legislators and political leaders, these should also be the starting point for aligning their interests with workable insurance markets and decreasing the risk of political and regulatory risk to the insurance industry. In a word, national governments should be considered a major group of new clients for risk professionals concerned with offering products and services to assess and cope with the risks of climate change.

Products and Services for Clients in Developing Countries

In the developing world, where more than 3 billion people live on less than \$2 per day (Munasinghe, 2009), the impacts of climate change are potentially disastrous. Here insurance can play an important role in mitigating the effects of major disasters, through modeling and information services, and through Alternative Risk Transfer instruments with parametric triggers or other indexed and securitization instruments that are contracted for with the government (see Brahin et al., 2009; Linnerooth-Bayer et al., 2009). Micro-insurance in the mid-level developing countries will also be feasible in the future to provide immediate cash infusions to small business owners after an event (Warner and Spiegel, 2009). Increasingly, catastrophe modeling capabilities, coupled with GIS, will be needed to predict and support responses to the major humanitarian disasters and migrations that will follow climate change impacts for developing countries that are especially vulnerable. I hesitate to refer to the benefits derived from these services as an opportunity, but considering the likely scenarios in their absence, the payoff from using insurance industry capabilities to predict and cope with climate change in the developing world is obviously huge. A problem will be how to fund the research needed to support data and model development. There is minimal financial incentive for the major commercial modeling firms to self-fund the research needed to create data systems and relevant model refinements, given the low insurance penetration in these regions. For this reason, initial funding will need to come from governments and organizations with economic and humanitarian interests in the affected areas. Moving ahead in the developing world will require a real push from the insurance industry to move public-private partnerships. The Munich Re Insurance Initiative (MCII) submitted for consideration in the Copenhagen COP15 Climate Change Meetings is a major initiative in this regard¹⁸. The MCII framework foresees as a first step quantification of the expected losses for developing countries seeking international support for adaptation and recovery funds from the international community.

¹⁸ See Linnerooth-Bayer, Bals and Mechler (2009) for a detailed discussion of the MCII framework and a general discussion of climate adaptation strategies.

Conclusion

For climate change risks, lagging indicators based on normal data-driven science and falsification methods will not, on their own, provide a sufficient basis for timely action in responding to climate change. There must be a much tighter relationship between the scientific community concerned with climate change and those concerned with the financial consequences of potential disasters resulting from climate change. Climate change is systemic and global and any effective framework to manage the associated risks of climate change must therefore recognize the interdependencies on the current global economic order. Given the stakes and the competencies required, and echoing Hata (2009), the insurance industry should take a leadership role in the global debate on how to confront these risks. This leadership role should encompass the following:

- Leadership in terms of establishing the insurance industry as a critical partner in this arena. It should do so by providing convincing examples of where and how insurance is adding value in terms of risk management services, in terms of generating knowledge to support company and country decision making, and in terms of facilitating needed change and adaptation where it would otherwise not occur.
- Leadership in designing national and global social contracts that address the risks of climate change, sharing the burdens equitably, and with a horizon long enough to properly value the magnitude of impacts we are likely to face under climate change and the nature of mitigation and adaptation measures necessary to cope with these impacts.

Undertaking this leadership role will also necessarily require innovations in products and risk management services, which the insurance industry has already developed over the past two decades including weather derivatives and other securitized instruments that will help to access risk-bearing capital. Other customer-driven innovations should include the following:

- Innovation in terms of the developing world where the largest impacts of climate change will occur. These innovations must encompass acquisition of better data on hazards and property/lives at risk, as well as the means for financing mitigation and adaptation that make sense for the developing world and simultaneously also contribute to achieving global targets for GHG emissions.

- Innovation in terms of national planning that assists country planners and emergency response organizations to understand in an integrated fashion the full landscape of correlated risks they will see as climate change impacts begin to take traction.
- Innovation in terms of integrated risk management services for companies, especially those with tighter ties to areas likely to be more strongly affected by climate change (e.g., the global retail industry) that allow companies to understand climate change, to integrate this with sustainability strategies and to prevent, prepare and reserve for risks they will confront.

A fundamental question raised by all the above is how the insurance industry should approach the most important new client group for climate change risks, national governments. The insurance has the competence to quantify weather-related risks for various assets vulnerable to climate change risks and to design appropriate products and services to package these and transfer them. Working with the scientific community to understand the impact of the remaining significant uncertainties associated with these risks, and with governments to assure that they understand the expected losses they own, will surely be one of the main challenges for the industry in the decade ahead.

Acknowledgement

Research on this paper was supported by the Paul Dubrule Chair at INSEAD and by the INSEAD Social Innovation Centre. Discussions with George Walker on the general problem of insuring climate change risks and with Howard Kunreuther and Joanne Linnerooth-Bayer on multi-period insurance instruments and adaptation policies for emerging economies are gratefully acknowledged. All of the shortcomings of this paper rest squarely with the author.

Technical Appendix

This appendix provides additional material on the two examples discussed in the text, the first concerning a private agent's assessment of decisions related to insurance and mitigation options and the second concerning an insurer's decision on capital requirements.

Insurance and Mitigation Decisions for an at-risk Private Party under Ambiguity

We consider an agent with both risk preferences and ambiguity preferences, following the axiomatic structure developed by Klibanoff, Marinacci and Mukerji (KMM) (2005). We consider the simplest version of the KMM model in which the loss distribution is known, but the probability of

occurrence of a loss event is ambiguous. Denote by $L(x)$ the losses suffered by the agent in the event of a loss, which is assumed to be decreasing in the level of the agent's ex ante investment x in insurance and mitigation. At most one loss per period occurs and this occurs with probability $p \in [0,1]$. The probability itself is "vague" or ambiguous, and assumed to lie in the interval $[p_0 - \delta(y), p_0 + \delta(y)]$, where y is the investment made in knowledge acquisition, so that the level of uncertainty captured in $\delta(y)$ is decreasing in y . Let us assume further that the agent believes that the ambiguous probability $p(y)$ is uniformly distributed over the interval $[p_0 - \delta(y), p_0 + \delta(y)]$.

The KMM model can be expressed as follows for this problem:

$$\text{Maximize } E_{p(y)}\{\varphi(E_{L(x)}\{U(W - x - L(x) - y)\})\} \quad (1)$$

where W is the agent's initial wealth, the maximization is over x and y and where φ represents the agent's preferences for ambiguity and U represents the agent's risk preferences. If $L(x)$ is decreasing and convex, representing decreasing returns to scale for investments in insurance and mitigation, and if the agent is both ambiguity averse and risk averse (or risk neutral), then at optimum investments in epistemic risk reduction (y) will increase as ambiguity aversion increases and mitigation and insurance investments (x) will increase as either ambiguity aversion or risk aversion increases. A simple case of the above would assume U to be risk neutral, $L(x) = c/x$ and $\delta(y) = \delta_0 e^{-ay}$, for some parameters $c, d > 0$ and $\delta_0 \in [0, p_0]$, with ambiguity preferences following the CARA form $\varphi(u) = -e^{-au}$, with $a > 0$ representing the degree of ambiguity aversion. In this case, problem (1) would take the form:

$$\text{Maximize } \int_{p_0 - \delta(y)}^{p_0 + \delta(y)} \left[-\frac{e^{-a(W-x-\frac{c}{p})}}{2\delta_0 e^{-ay}} \right] dp \quad (2)$$

The basic intuition behind this model is that ambiguity preferences are confounded with risk preferences and this leads to an interaction between investments in reducing ambiguity and investments to reduce losses.

Capital Requirements for Catastrophe Insurance

Consider a particular insurer doing business with cat exposure in a specified region, e.g., the State of Florida. Denote by $x = (x_1, x_2, \dots, x_n)$ the vector of exposures for the insurer, where x_i is the insurer's exposure in insurance zone i in the region. In keeping with the notion that the insurance market is workably competitive, we assume that the firm is a price-taker in the market, with price in zone i per unit of exposure given by p_i . We can therefore focus only on the amount

of business x_i the insurer chooses to write in each zone i . Let $L_i(x_i)$ be the random variable representing losses in zone i and let $L(x) = L_1(x_1) + L_2(x_2) + \dots + L_n(x_n)$ denote total losses. Losses in different zones may be correlated since the same event could create losses in more than one zone. Losses to different properties within a zone are correlated for the same reason. These losses may arise from catastrophe lines of business or from other lines. Such losses would be estimated using one of the several catastrophe models available (see Grossi and Kunreuther (2005) for a discussion of cat models).

Denote by $\Pi(x, A, B)$ the expected profits for the insurer for a typical year, where A are the assets of the insurer supporting the business x and B is additional risk-bearing capital in the form of reinsurance, bonds and capital from other non-premium sources. We can write expected profits as:

$$\Pi(x, A, B) = R(x) - M(x) - \bar{L}^*(x, A, B) - rB = \sum_{i=1}^n [R_i(x_i) - M_i(x_i)] - \bar{L}^*(x, A, B) - rB \quad (3)$$

where

$R_i(x_i)$ = Annual revenue from zone $i = p_i x_i$

$M_i(x_i)$ = Marketing, Sales and Distribution (annual) Expenses for zone i

$\bar{L}^*(x, A, B) = E\{\text{Min}[L(x), (R(x) - M(x) + A + (1-r)B)]\}$ = Expected annual losses from all zones, truncated at the insolvency point $L^* = R(x) - M(x) + A + (1-r)B$.

rB = Payments to capital providers for B

Marketing expenses M_i will depend on company organizational variables such as its distribution system. We will think of B as reinsurance, but B could also be in the form of zero-coupon bonds. The important assumption we make about B is that the premium (or interest in the case of bonds) is prepaid, before losses are known, so that $(1-r)B$ is actually available to pay losses if B units of reinsurance are purchased. The shareholder equity A that the insurer puts at risk may influence the rate r or the amount of reinsurance B obtainable. We take A and r as fixed here and assume that B is set to just satisfy a solvency constraint, specified below.

Once A and B are exhausted, i.e., insolvency occurs, the insurer bears no further responsibilities for losses; losses are therefore accounted for in the expected profit function only up to the point of insolvency. Following Greenwald and Stiglitz (1990), based on transactions costs of insolvency and the franchise value of the firm going forward, solvency constraints may be viewed as an endogenous outcome of the options value of continued operations. The price of the option in this case is the differential returns to capital devoted to the insurance business at the margin rather than to other market opportunities. An alternative and equivalent approach to making insolvency probabilities endogenous, driven by an exogenously specified franchise value

of the firm going forward, is to take the level of insolvency probability as exogenous. This is the approach I take here. It is the usual approach undertaken in the catastrophe insurance area in constraining underwriting and reserving policies to achieve a specified level of insolvency.

These considerations lead to the standard model in which the insurer chooses its book of business x to maximize $\Pi(x, A, B)$ subject to a solvency constraint based on a probable maximum loss (PML). If r is the cost of additional capital B , then this requires that underlying reserves and additional capital $K = A + (1-r)B$ be set large enough to avoid financial distress with a probability exceeding $1 - \rho$, where ρ represents the worst case or planned Probable Maximal Loss (PML) probability. Formally, we have the requirement:

$$\Pr\{L(x) > R(x) - M(x) + A + (1-r)B\} = EP[R(x) - M(x) + A + (1-r)B; x] \leq \rho \quad (4)$$

where $EP(L; x) = \Pr\{L(x) > L\}$ is the exceedance probability curve for the given book of business x , and where $R(x)$ and $M(x)$ are premium revenues and marketing expenses of the insurer for the chosen book of business x . The insurer's problem of interest is to choose x to maximize $\Pi(x, A, B)$ in (3) subject to (4). In graphical terms, this corresponds to the problem of adjusting $K = A + (1-r)B$ and the portfolio x (and with it the EP curve $EP(L(x), x)$) to achieve the desired level of PML coverage. Note that the characteristics of the portfolio x are clearly important in determining the EP curve for this problem-- the more highly correlated interzonal losses are, the fatter the tail of the EP curve and the larger the required surplus. The discussion in the text makes the basic point that if there is considerable uncertainty about the EP curve itself, then loss distribution fat-tails and related reserving issues will be further complicated.

REFERENCES

- Beck, U. 1992. *Risk Society*, London: Sage Publications.
- Berliner, B. 1982. Limits of Insurability of Risks. Englewood Cliffs, NJ, Prentice-Hall.
- Bernstein, R. I. 1983. *Beyond Objectivism and Relativism*. Philadelphia: University of Pennsylvania Press.
- Brahin, P., D. Bresch, R. Schnarwiler and R. Tanner 2009. *Country Risk Management: Making Societies More Resilient*. Zurich: Swiss Reinsurance Company.
- Brekke, K. A. and O.Johansson-Stenman 2008. The Behavioral Economics of Climate Change, Working Paper, University of Gothenburg, May.
- CCS (Consortio de Compensación de Seguros). 2008. *Natural Catastrophe Insurance Cover: A Diversity of Systems*. CCS, Madrid.
- Clark, K. 2007. Managing Changing Catastrophe Models. *Managing the Changing Landscape of Catastrophe Risk (Proceedings of the 10th Aon Re Australia Biennial Hazards Conference)*. Sydney: Aon Re Australia Ltd.
- Cottrell, N. B. 1968. Performance in the Presence of Other Human Beings. In E. C. Simmel, R. A. Hoppe and G. A. Milton (eds), *Social Facilitation and Imitative Behavior*. Boston: Allyn & Bacon, 91-110.
- Curley, Shawn, Frank Yates and R. A. Abrams 1986. "Psychological Sources of Ambiguity Avoidance." *Organizational Behavior and Human Decision Processes*. Vol 38, 230-256.
- Easterling, D. and H. C. Kunreuther 1995. *The Dilemma of Siting a High-Level Nuclear Waste Repository*, Boston: Kluwer Academic Publishers.
- Fischhoff, B. 1991. Value elicitation: Is there anything in there? *American Psychologist*, 46(8), 835-847.
- Garnaut, R. 2008. *The Garnaut Climate Change Review*. Cambridge: Cambridge University Press.
- Geneva Association. 2009. *The Insurance Industry and Climate Change*, Geneva: The Geneva Association (July).

Grace, M. F., R. W. Klein and P. R. Kleindorfer. 2004. The Demand for Catastrophic Insurance, *J. of Risk and Insurance*, Vol. 71, pp. 351-379.

Greenwald, B. C. and J. E. Stiglitz 1990. Asymmetric Information and the New Theory of the Firm: Financial Constraints and Risk Behavior, *American Economic Review*, 80, 106-165.

Grossi, P. and H. Kunreuther (eds) 2005. *Catastrophe Modeling: A New Approach to Managing Risk*, Boston: Kluwer Academic Publishers.

Habermas, J. 1973. *The Legitimation Crisis*. Boston: Beacon Press.

Harrington, K. and J. O'Connor, 2009. How Cisco Succeeds at Global Risk Management, *Supply Chain Management Review*, July. Available at: <http://www.scmr.com/article/CA6672233.html>

Hata, H. 2009. Leadership by Insurance: How the Insurance Industry Can Establish Best Practices in Its Business Models Related to Climate Change. Chapter 8 in Geneva Association (2009).

Heath, C. and A. Tversky 1991. Preference and Belief: Ambiguity and Competence in Choice, *Journal of Risk and Uncertainty*, Vol. 4, pp. 5-28.

Heck, P., D. Bresch and S. Troeber 2006. *The Effect of Climate Change: Storm Damage in Europe on the Rise*. Zurich: Swiss Reinsurance Company.

IMF (International Monetary Fund) 2008. Climate Change and the Global Economy, in *World Economic Outlook April 2008*. Washington DC: IMF.

Jasanoff, S. (ed) 2004. *States of Knowledge: The Co-production of Science and Social Order*, New York: Routledge.

Kleindorfer, P. R. 2009a. Reflections on Decision Making under Uncertainty, forthcoming in F. Diebold, N. Doherty and R. Herring (eds), *The Known, the Unknown and the Unknowable in Financial Risk Management*. Princeton: Princeton University Press.

Kleindorfer, P. R. 2009b. Legitimation in Decision Making, forthcoming in Erwann Michel-Kerjan and Paul Slovic (eds), *The Irrational Economist: Making Decisions in a Dangerous World*, New York: Public Affairs Books.

Kleindorfer, P. R. 2009c. Climate Change and Insurance: Integrative Principles and Regulatory Risks, Working Paper, INSEAD, available at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1456862

Kleindorfer, P. R. and R. W. Klein. 2003. Regulation and Markets for Catastrophe Insurance, in Murat R. Sertel and Semih Koray (eds), *Advances in Economic Design*, Heidelberg: Springer Verlag.

Kleindorfer, P. R., H. C. Kunreuther, E. Michel-Kerjan and R. Zeckhauser 2008. Mitigating and Financing Catastrophic Risks: Principles and Action Framework; Discussion Document, International Network on Financial Management of Large-Scale Catastrophes, Paris: OECD.

Kleindorfer, P. R., H. C. Kunreuther, and P. J. Schoemaker 1993. *Decision Sciences: An Integrative Perspective*, Cambridge University Press.

Kleindorfer, P. R. and J. Wind 2009. *The Network Challenge: Strategy, Profit and Risk in an Interlinked World*. Wharton Publishing Company, Upper Saddle Creek, NJ.

Klibanoff, P., M. Marinacci, and S. Mukerji 2005. A Smooth Model of Decision Making under Ambiguity, *Econometrica*, 73: 1849-1892.

Knutson, T. R. 2008. Global Warming and Hurricanes: An Overview of Current Research Results. Geophysical Fluid Dynamics Laboratory/NOAA . At <http://www.gfdl.noaa.gov/global-warming-and-hurricanes>

Kousky, C., O. Rostapshova, M. Toman and R. J. Zeckhauser, Responding to Threats of Climate Change Mega-Catastrophes (November 1, 2009). World Bank Policy Research Working Paper Series, Vol. , pp. -, 2009. Available at SSRN: <http://ssrn.com/abstract=1509194>

Kuhn, T. S. 1996. *The Structure of Scientific Revolutions* (3rd Edition). Chicago, IL: The University of Chicago Press.

Kunreuther, H. C. 2009. Long-Term Insurance and Climate Change. Working Paper # 2009-03-13, Wharton Risk Management and Decision Processes Center, University of Pennsylvania. At http://opim.wharton.upenn.edu/risk/library/WP2009-03-13_HK_LTI.pdf.

Kunreuther, H. C. and E. Michel-Kerjan 2009. *At War with the Weather*. Cambridge: MIT Press.

- Linnerooth-Bayer, J., M. J. Bals and R. Mechler 2009. Insurance as part of a Climate Adaptation Strategy, in M. Hulme and H. Neufeldt (eds). *Making Climate Change Work for Us: European Perspectives on Adaptation and Mitigation Strategies*. Cambridge: Cambridge University Press.
- Linnerooth-Bayer, J., K. Warner, C. Bals, P. Höpfe, I. Burton, T. Loster and A. Haas 2009. “Insurance, Developing Countries and Climate Change.” *The Geneva Papers*, **34**, 381–400.
- Munasinghe, M. 2009. *Sustainable Development in Practice*. Cambridge: Cambridge University Press.
- Mansanet-Bataller, M. and A. Pardo 2008. What You Need to Know to Trade in CO2 Markets. Mission Climat de la Caisse des Dépôts, Paris. At <http://ssrn.com/abstract=1156973>.
- Miller, S., R. Muir-Wood and A. Boissonnade. 2008. An Exploration of Trends in Normalized Weather-related Catastrophe Losses. In H. F. Diaz and R. J. Murnane (eds), *Climate Extremes and Society*. Cambridge: Cambridge University Press.
- Mills, Evan. 2009. A Global Review of Insurance Industry Responses to Climate Change. *The Geneva Papers*, Vol. 34, 323–359.
- Munich Re 2009. Natural catastrophes 2008: Analyses, Assessments, Positions. Munich : Munich Re Group.
- OECD (Organization for Economic Cooperation and Development). 2009. Innovation in Country Risk Management. OECD, Paris.
- Papadakis, I. S. And W. T. Ziemba. 2001. Derivative Effects of the 1999 Earthquake in Taiwan to U. S. Personal Computer Manufacturers, in P. R. Kleindorfer and M. R. Sertel (eds.), *Mitigation and Financing of Seismic Risks: Turkish and International Perspectives*, Kluwer Academic Publishers, Boston, 2001.
- Popper, K. 2002. *The Logic of Scientific Discovery*. London: Routledge Classics.
- Schelling, T. C. 2006. *Strategies of Commitment*. Harvard University Press, Cambridge.
- Simonson, I. and P. Nye 1992. The Effect of Accountability and Susceptibility on Decision Errors. *Organizational Behavior and Human Decision Processes*. 51, 416-446.
- Slovic, P. 1987. Perception of Risk. *Science*, 236, pp. 280-285.
- Stern, N. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge: Cambridge University Press.
- Stern, N. 2008. The Economics of Climate Change, *American Economic Review*, May, 98(2), 1-37.

Stone, James. 1973. "A Theory of Capacity and the Insurance of Catastrophe Risks," *Journal of Risk and Insurance*, pp. 40:231-243, 337-355.

Swiss Re/ProClim 2009. SwissRe/ProClim Climate Fact Sheets (No. 1) (2nd ed.): Influence of global warming on tropical cyclones (Hurricanes, Typhoons). Zurich: Swiss Reinsurance Company.

Taleb, N. N. 2007. *The Black Swan: The Impact of the Highly Improbable*. New York: Random House.

van den Broeke, M. J. Bamber, J. Ettema, E. Rignot, E. Schrama, W. Jan van de Berg, E. van Meijgaard, I. Velicogna and B. Wouters. 2009. Partitioning Recent Greenland Mass Loss. *Science* (13 November 2009): Vol. 326, No. 5955, pp. 984-986.

von Ungern-Sternberg, T. 2004. *Efficient Monopolies: The Limits of Competition in the European Property Insurance Market*. Oxford: Oxford University Press.

Warner, K. and A. Spiegel. 2009. Climate Change and Emerging Markets: The Role of the Insurance Industry in Climate Risk Management. Chapter 7 in Geneva Association (2009).

WEF (World Economic Forum) 2008. *CEO Climate Policy Recommendations to G8 Leaders*. Geneva: World Economic Forum.