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Abrupt Climate Change: Lessons from Integrated Catastrophic Risk Management

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Contents

Abstract

This paper is an extended version of the talks “Uncertainty and Robust Solutions: Lessons from IIASA Case Studies on Catastrophic Risk Management and Economic Growth under Shocks” given on 12 June 2002 and “Sink Technologies and Climate Risk Management” given on 15 May 2002 at IIASA’s Greenhouse Gas Initiative seminars (see web site: www.iiasa.ac.at/~marek/ggi/).

Risks of disaster arise out of the combination of natural hazards and human activities. We argue that by divorcing the natural disaster issues from social and economic development, half of this disaster equation is ignored. The current pace of disaster development is undermining the markets and safety nets not only of developing countries. Far greater policy coherence is needed between economists, development planners, natural scientists and disaster managers in order to prevent catastrophic losses to human lives, livelihoods, and natural and economic assets.

In this paper we present an integrated approach to catastrophic risk management that aims at more coherence and comprehensiveness. The models presented take into account spatial and temporal heterogeneity of catastrophes as well as institutional heterogeneity within a model of economic growth. Loss and gains profiles are functions of various strategies/requirements/goals of agents such as individuals, governments, producers, insurers and investors. GIS-based catastrophe models and stochastic optimization methods allow to guide policy analyses with respect to location specific risk exposures.

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About the Authors

Tatiana Ermolieva is a Research Scholar in IIASA's Forestry Project. In 1997, she was awarded the Kjell Gunnarson's Risk Management Prize of the Swedish Insurance Society for the paper "Spatial Stochastic Model for Optimization Capacity of Insurance Networks under Dependent Catastrophic Risks" (see Ermolieva *et al*., 1997). The same year she was awarded IIASA's Peccei Scholarship for her research during the 1997 Young Scientists Summer Program (YSSP), which resulted in the paper on "Design of Optimal Insurance Decisions in the Presence of Catastrophic Risks" (see Ermolieva, 1997).

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Abrupt Climate Change: Lessons from Integrated Catastrophic Risk Management

Tatiana Ermolieva and Michael Obersteiner

1 Background on Climate Risk Management

Much of the debate on climate change is based on a scientific understanding that the climate will change gradually and incrementally. In fact, until a few decades ago it was generally thought that all large-scale global and regional climate changes occurred gradually over a timescale of many centuries or millennia, scarcely perceptible during a human lifetime. Almost all prominent economic assessment models today are deterministic and fail to account for the uncertainties in climate change and do not take into account the inherently abrupt nature of the climate leading to extreme climate events.[1] This might also be the reason why there are only very loose ties between the climate change and the risk and natural disaster communities.

The ill-tempered nature of the "beast" climate, exhibiting relatively sudden changes, has been one of the most surprising outcomes of the most recent study of the earth's history (Taylor *et al*., 1993). The economic profession and policy makers have so far ignored this scientific fact. Today, numerous studies on paleo-climatic proxies give evidence that climate change has been abrupt and disruptive to ecological systems and societies on large or even global scales (NRC, 2002). The time span of the past few million years has been punctuated by many rapid climate transitions, most of them on time scales of centuries to decades or even less. Detailed analysis of terrestrial and marine records of climate change will, however, be necessary before we can confidently say on what timescale these events occurred; they almost certainly did not take longer than a few centuries (Adams *et al*., 1999). Another under-researched issue is the geographic extent and distribution of punctuated climate events.

Various mechanisms, involving orbital forcing, volcanic activity, changes in ocean circulation, changes in atmospheric concentrations of greenhouse gases or haze particles, and changes in snow and ice cover have been invoked to explain these sudden regional and global transitions — some of which are outside human influence and as such can not be managed. It is still unclear how the climate, on a regional or even global scale, can change as rapidly as present evidence suggests. It appears that the climate

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[1] Well-known models in the literature include the DICE model (Nordhaus, 1993) and the global 2100 model (Manne and Richels, 1992). For a survey see, e.g., the Energy Journal (1999). Notable and very recent examples are Mastrandrea and Schneider (2001) and Heal and Kriström (2002) both of which present rather stylized models and fail to model climate risk by appropriate stochastic processes.

system exhibits chaotic properties and is more delicately balanced than previously thought, linked by a cascade of powerful mechanisms that can amplify a small, maybe untraceable and unknown, initial change into much larger shifts in climate parameters. It is precisely the abruptly changing nature of the climate that requires new paradigms to approach the problem of climate change in the long run. Most of the traditional economic approaches are inappropriate in situations of such extreme uncertainty and risk. Surprises are inevitable, however, and the magnitude and frequency of sudden changes are affected and, to a certain extent, managed by human influence. This is the core of our interest in this paper and we will review the most recent advances in catastrophic risk modeling and management in order to investigate the possible transfer of this knowledge and tools for managing abrupt climate systems change.

As researchers, it is not only uncertainty about the underlying climate science that should concern us. Ultimately, we are interested in the impact of climate change on human societies, which involves knowing not only about how the climate may alter but also about how changes in the climate regime translate into impacts that matter to humans in a direct or even an indirect way. How do climate changes translate into changes in agricultural production (food security),[2] into changes in the ranges of disease vectors, into changes in patterns of tourist travel, or even into feelings of well-being directly associated with the state of the climate? Even if we knew exactly what the climate would be in 2100, we would still face major economic uncertainties because we do not currently know how altered climate states map into human welfare.

In summary, there are at least three different kinds of uncertainty that should be taken into account, namely, scientific, impact and policy uncertainties. The instruments of possible policy responses to climate change take two forms (for an overview, see Obersteiner *et al*., 2001): *mitigation*, i.e., actions that reduce the flow of greenhouse gases into the atmosphere and, thereby, change the probability distribution over future climate states; and *adaptation*,[3] actions that reduce and redistribute the damages associated with a given climate state within a society. Both forms provide sources of uncertainty with respect to their implementation and their effectiveness when implemented. In the domain of mitigation, perhaps the most prominent sources of uncertainties are institutional and technological. Will the international community adopt aggressive mandates to restrict emissions of greenhouse gases? Will mitigation measures be effective in the sense that they reduce climate hazard? Will the institutions that implement these mandates be efficient, i.e., will the marginal cost of net reductions in emissions be roughly equal across all sources and sinks? What technical changes will appear to reduce the costs of mitigation? Likewise, adaptation involves uncertainty about the different options that will become available, and their costs. As a particular

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[2] A newly released IIASA report (see Fischer *et al*., 2002) integrates spatial agro-ecological evaluations of all countries, developed and developing, into a world economy and trade policy general equilibrium model. While elevated greenhouse gas concentrations in the atmosphere and associated global warming will result in improved agricultural potential for some (mainly developed) countries, a large number of poor and food-insecure developing countries may lose a significant proportion of their agro-ecological production potential.

[3] Note that the risk community uses the term 'mitigation' for both mitigation and most adaptation measures defined by the climate community.

adaptation strategy, the role of the financial industry and its climate change related instruments is crucial in this respect.

With respect to uncertainty the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) goes further and recognizes no less than five stages of uncertainty, which is the result of breaking down the scientific uncertainty into sub-categories (IPCC TAR, 2001). These five categories are uncertainty about emission scenarios (i.e., about anthropogenic emissions of greenhouse gases[4]), about the responses of the carbon cycle to these emissions, about the sensitivity of the climate to changes in the carbon cycle, about the regional implications of a global climate scenario, and finally uncertainty about the possible impacts on human societies. The TAR has a diagram showing the degree of uncertainty rising as we move through these five stages, with the error bars growing from stage to stage.

Uncertainty is pervasive in the analysis of climate change. Uncertainty can of course be reduced through learning. This consideration leads to a second-order, or meta-form of uncertainty — what new information will be revealed to resolve present uncertainties? To what extent can and will research accelerate the pace of learning? Given future learning possibilities, the issues of irreversibility and quasi-option value may become salient. This discussion clearly suggests that any economic analysis of climate change should include uncertainty as a central feature. Yet current assessment literature shows that the bulk of the work to date has been deterministic, though there are exceptions and the trend is changing.

If uncertainty is central then attitudes towards risk and the degree of risk aversion will presumably be central parameters. Institutions for risk-shifting will also be important (in particular with respect to the "news" of abrupt climate change), as will the possibility that some changes are irreversible, which will most likely be the case with abrupt climate change, and that we may learn more about them with the passage of time suggests that real option values may also matter in the analysis of policy measures. In this respect, the notion of currently existing models using truncated forms of uncertainty that is, in fact, treated as certainty needs to be renounced in order to guarantee the robustness of policies and institutions. Another analytically interesting feature of climate change is that the risks are not exogenous, as in many models of uncertainty in economics, but are generated by our own activities. This endogeneity of risks raises questions about the use of markets and insurance for hedging some of the risks associated with possible climate change — there is the macro-level equivalent of moral hazard here. Finally, as many authors have remarked, the time horizon that is implicit in climate change is very long indeed and, measured in centuries, it is far longer than economists are used to. Uncertainties are almost inevitably large when decisions involve such long time horizons, despite the fact that abrupt climate change can take place over time spans of years or decades. In summary, therefore, in analyzing climate change policies, our attitudes towards risk will be important as perhaps will the values of maintaining certain options open. Our research will be able to provide the analysis of the impact of risk averseness versus risk prone strategic postures with respect to climate change.

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[4] IIASA provided pioneering work in this respect, see Gritsevskii and Nakicenovic (2000).

Endogeneity of risks may pose some problems for the use of certain types of financial institutions, and the length of the time horizon will pose a challenge to our normal ideas about discounting. A very general model that incorporates most of the central issues is still lacking. Certainly, a model that takes abrupt climate change seriously and accounts for endogeneity of risk is too complex to be solved analytically as rare and dependent events have to be incorporated in the model structure. IIASA has a long tradition in solving these kinds of "insurmountable" analytical problems.

In this paper, we will look at a range of issues relating to the management of climate risks by economic institutions such as financial markets in combination with climate mitigation and adaptation measures, the impact of uncertainty and the endogeneity of risks, and we will describe the methodological approach and pathway to solve this problem. Furthermore, we will stress the importance of geographic and temporal clustering of hazards and their implication for robustness of risk management.

2 Background on Natural Disaster Risk Management

The possibility of more frequent extreme natural disasters dominates the discussions of current global changes. Climate models used by the IPCC for projecting climate change predict various negative effects due to increased anthropogenic CO_2 emissions. One of the main negative inferences is the possibility of increased frequency, severity, and duration of such extreme natural hazards as *inter alia* more hot days, heat waves, precipitation events, tornados and thunderstorms. While fluctuations in temperature changes are well established (see, e.g., IPCC TAR, 2001) changes in precipitation regimes are not as well researched. A rather recent study by Milly *et al*. (2002) found that the frequency of severe floods in large river basins has increased during the 20th century. Another study by Palmer and Raisanen (2002) analyzed the output of 19 climate models, and predicted that wet winters will be five times more likely in northern and central Europe over the next century.

A shift in the overall hazard exposure due to the occurrence of more frequent extreme events will lead to more frequent economic and social shocks at national and regional levels with possible consequences to the global economy. Although these shocks on average may not seem to be significant and are usually ignored within standard economic models, severe economic stagnation and instability of some regions may result from changes in the magnitude and frequency of extreme events. In particular, natural disasters in developing countries will be more catastrophic and more costly in human lives, all of which will possibly contribute to underdevelopment traps.

There is an interesting paradox of increasing losses from natural catastrophes — there is agreement that global risk exposure is becoming unsustainable and an inability to stop the growth of human and economic losses. The main structural reasons for increasing losses are the clustering of people and capital in hazard-prone areas as well as the creation of new hazard-prone and hazard creating areas. This is attributing to the increasing return phenomenon combined with the ignorance of rare-high consequence risks. On the social side, there are a number of reasons why there is a 'supply shortage' of loss reducing disaster management that are due to the public good character of providing disaster management, high social discounting in geography and time of extreme events, and the complex and uncertain nature of the issue. Thus, current disaster trends are likely to continue to undermine the markets and safety nets of developing and developed countries.

Catastrophes produce losses that are highly mutually dependent in space and time. This characteristic challenges the standard risk pooling concepts and the standard extremal value theory (Embrechts *et al*., 2000). The law of large numbers does not operate (in general), and the probability of ruin can be reduced not by just pooling risks, but only if insurers deliberately select the dependent fractions of catastrophic risks they will cover. The existing extremal value theory also deals primarily with independent events, assuming these events are quantifiable by a single number. Catastrophes are definitely not quantifiable events in this sense. They may have quite different spatial and temporal patterns, which cause significant heterogeneity of losses in space and time. These losses can be dramatically affected by risk mitigation decisions and loss spreading schemes within a country or on the international level through the insurance or financial markets.

The main question in connection with catastrophes is the management of losses. Until recently, they were mainly absorbed by the immediate victims and their governments (Gilber and Gouy, 1998; Linnerooth-Bayer and Amendola, 2000). The insurance industry and its premium payers (and investors) also absorb a portion of catastrophic losses, but even in the wealthy countries this share is relatively small. As current losses increase, the governments are concerned with escalating costs for disaster prevention, response, compensation to victims, and public infrastructure repair. It is important to increase the responsibility of individuals and local governments for the risks and their consequences. Local governments may be more effective in the evaluation and enforcement of loss-reduction and loss-spreading measures, but this is possible only through location-specific analysis of potential losses, the mutual interdependencies of these losses, and the sensitivities of the losses to new land use and other risk management strategies.

In the following text we discuss an integrated framework that enables us to analyze spatial and temporal heterogeneity of various agents (stakeholders) induced by mutually dependent losses from extreme events. The model explicitly addresses the specifics of catastrophic risks — the lack of information, the need for long-term perspectives and geographically explicit models, and the involvement of various agents such as individuals, governments, farmers, producers, consumers, insurers, reinsurers, and investors. The model combines geographically explicit data on the distribution of properties in a studied region with a stochastic catastrophic model generating magnitudes, timing, and location of catastrophes. The integrated catastrophic risk management approach, as presented in this paper, is likely to offer more coherent, comprehensive and robust policy responses. Coherence is needed between economists, development planners, natural scientists and disaster managers; and comprehensiveness is required in order to identify the policy gaps between the existing measures in place compared to those needed to guarantee economic development that is robust against shocks from catastrophes. For these purposes, the model embeds the stochastic optimization procedure that allows to analyze robust optimal portfolios of ex-ante (land use, structural mitigation, insurance) and ex-post (adaptation, rehabilitation, borrowing) measures for decreasing regional vulnerability measured in terms of economic, financial, and human losses as well as welfare growth indicators. The approach is illustrated in recent case studies of seismic and flood risk management.

3 A Simple Risk Management Model

Catastrophic events such as floods, earthquakes, and windstorms occur abruptly in time and space as "spikes" that cannot be properly modeled on "average". The following risk management models address this "abruptness" feature of catastrophes.

Let us consider a simple model of growth under abrupt shocks, which is a stylized version of the insurance business (Borch, 1962; Daykin *et al.*, 1994; Grandell, 1991). The main variable of concern is the risk reserve r^t at time t: $r^t = r_0 + \pi^t - A^t$, $t \geq 0$, where π^t, A^t are aggregated premiums and claims, and r_0 is the initial risk reserve. The process $A^t = \sum_{k=1}^{N(t)} S_k$, where $N(t)$, $t \geq 0$ are a random number of claims in interval $[0,t]$ (e.g., a Poisson process) with $N(0) = 0$, and $\{S_k\}_1^\infty$ is a sequence of independent and identically distributed random variables (claims) — in other words, replicates of a random variable S. In this model, the inflow of premiums π^t pushes r^t up, whereas the random outflow A^t pushes r^t down.

The main problem of catastrophic management is to avoid the situation when r^t drops abruptly below the "vital" level (ruin) — in our example, equal to 0. It is definitely only possible with a certain probability $\Psi = P\{r^t \leq 0 \text{ for some } t,\ t > 0\}$.

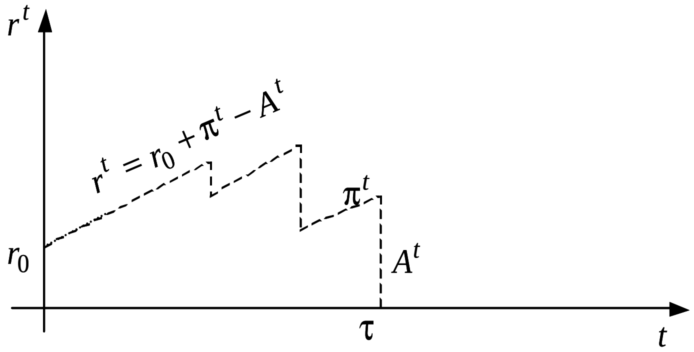

Figure 1: Trajectory of the risk reserve r^t subject to the random process of claims.

The deterministic approach is very simplified, as illustrated by the following calculations. Assume that $N(t)$, S_k, are independent, $N(t)$ has intensity α, i.e., $E\{N(t)\} = \alpha t$, and $\pi^t = \pi t$, $\pi > 0$. Then the expected profit over the interval $[0,t]$ is $(\pi - E(S)\alpha)t$, that is, the expected profit increases in time for $\pi - E(S)\alpha > 0$. Thus, the practical deterministic model ignores complex interdependencies among the timing of claims (temporal clustering), their sizes, and the subsequent possibility of ruin, $r^t \leq 0$. In this formulation the richer random jumping process r^t is replaced by a linear function in t, $r^t = r_0 + (\pi - \alpha ES)t$. The difference $\pi - \alpha ES$ is the "safety loading". It follows from the strong law of large numbers that $\left[\pi^t - A^t\right]/t \to \left[\pi - \alpha ES\right]$ with the probability of 1. Therefore, in the case of positive safety loading, $\pi > \alpha ES$, we have to expect that the real random profit $\pi^t - A^t$ for a sufficiently large t would also be positive under the appropriate choice of premium $\pi = (1+\rho)\alpha ES$, where ρ is the "relative safety" loading $\rho = (\pi - \alpha ES)/\alpha ES$. But this holds only if ruin does not occur before time t.

As illustrated in Figure 2, despite the fact that sustained growth of risk reserves r^t is guaranteed on average, the ruin of the real growth process may occur before sustained growth takes off. In other words, the substitution of the complex jumping process by a simple deterministic model (showing "robust" sustained growth) may lead to unforeseen collapses (surprises). In other words, only a stochastic model shows the necessity for a certain assistance of growth, at least in the form of such purely financial risk management measures as borrowing, contingent credits, or governmental bailouts. It is also possible to reduce the severity of the distribution of claims by various loss reduction mitigation measures. However, all of this is only possible by analyzing the probability of ruin Ψ. In general, various decision variables affect Ψ. The claim size S depends on the coverage of the insurer operating on geographically distinct locations. Important decision variables are r_0, π, and reinsurance arrangements. The reduction of Ψ to acceptable levels can be viewed as the so-called chance constraint stochastic optimization problem (see Ermoliev and Wets, 1988; Prekopa, 1995). The complexity is associated with the jumping process A^t with analytically intractable dependencies of A^t on decision variables, which requires specific stochastic optimization (STO) methods.

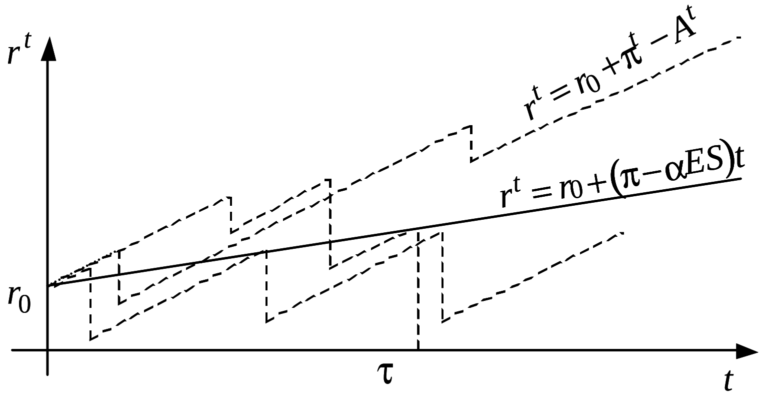

Figure 2: Expected and real growth of the risk reserve. There is an exit scenario due to an extreme event at time τ, which depletes the safety loading.

4 A Stochastic Integrated Catastrophe Management Model

Section 3 only briefly outlined some methodological complexities of the catastrophe management model. This section aims at a more comprehensive description of the inherent problem elements. A model for integrated catastrophe management consists, in principle, of two major submodels, a catastrophe model and an economic multi-agent model. The catastrophe model (earthquake, flood, etc.), is based on Monte Carlo simulations of geographically explicit catastrophe patterns and related direct losses in selected regions (a discussion of these models is beyond the scope of this paper but can be found elsewhere, see Amendola *et al*., 2000b; Baranov *et al*., 2002; Ermoliev *et al*., 2000a, b; Rozenberg *et al*., 2001; Walker, 1997). The economic multi-agent model is a multiregional stochastic dynamic welfare growth model (for the analyses of abrupt economic shocks see, e.g., Ermoliev *et al*., 2000a, b). This model maps spatial economic losses into gains and losses of agents. These agents are the central government, a mandatory catastrophe insurance (pool), an investor, "individuals" (cells or regions), producers (farmers), etc.

A catastrophe would ruin many agents if their risk exposures were not properly managed. To design safe catastrophic risk management strategies it is necessary to define location specific feasible decisions based on potential losses generated by a catastrophe model. Some of these decisions reduce the frequencies (likelihood) and magnitudes of catastrophic events (say, land-use decisions) and redistribute losses and gains on local and international levels (say, pools, insurance, compensation schemes, credits, borrowings). The crucial question is the use of appropriate risk measures, e.g., to avoid bankruptcy. Catastrophic losses often have a multimode distribution, and therefore the use of mean values (e.g., expected costs and profits) may be misleading. Roughly speaking, we cannot think in terms of aggregate regional losses and gains as the sum of location specific losses and gains (e.g., if the mean value is substituted by the median). Besides this, the number of alternative decisions may be very large. Thus, for a region with only 10 possible sub-locations and 10 alternative sizes of insurance coverage, the number of possible combinations is 10^{10}. The straightforward evaluation of all alternatives by calculating the damages of location specific values, etc., may easily exceed 100 years, which calls for the use of a spatial optimization technique that enables the design of desirable robust solutions without evaluating all of the possible alternatives. The model of this section reflects all this and it emphasizes the collective nature of catastrophe risk management.

Assume that the study region is divided into sub-regions or cells $j=\overline{1,m}$. A cell may correspond to a collection of households, a zone with similar seismic activity, a watershed, a grid with a segment of a gas pipeline, etc. The choice of cells provides a desirable representation of losses. For each cell j an estimate exists of its "wealth" at time t that may include the value of the infrastructure, houses, factories, etc. A sequence of random catastrophic events $\omega=\left\{\omega_t, t=\overline{0,T-1}\right\}$ affects different cells $j=\overline{1,m}$ and generates at each $t=\overline{0,T-1}$ mutually dependent losses $L_j^t(\omega)$, i.e., damages of wealth at j, T is a time horizon. These losses can be modified by various decision variables. Some of the decisions reduce losses, for instance a dike, whereas others spread them on a regional, national, and international level, e.g., insurance contracts, catastrophe securities, credits, and financial aid. If x is the vector of the decision variables, then losses $L_j^t(\omega)$ are transformed into $L_j^t(x,\omega)$. For example, we can think of $L_j^t(x,\omega)$ as $L_j^t(\omega)$ being affected by the decisions of the insurance to cover losses from a layer $[x_{j1}, x_{j2}]$ at a cell j in the case of a disaster at time t:

$$L_j^t(x,\omega) = L_j^t(\omega) - \max\left\{x_{j1}, \min\left[x_{j2}, L_j^t\right]\right\} + x_{j1} + \pi_j^t,$$

where $\max\left\{x_{j1}, \min\left[x_{j2}, L_j^t\right]\right\} - x_{j1}$ are retained by insurance losses, and π_j^t is the premium.

In the most general case, vector x comprises decision variables of different agents, including governmental decisions, such as the height of a new dike or a public compensation scheme defined by a fraction of total losses $\sum_{j=1}^m L_j^t$. The insurance decisions concern the premiums paid by individuals and the payment of claims in the case of a catastrophe. There are complex interdependencies among these decisions, which call for the cooperation of agents. For example, the partial compensation of catastrophe losses by the government enforces decisions on loss reductions by individuals and, hence, increases the insurability of risks, and helps the insurance to avoid insolvency. On the other hand, the insurance combined with risk-reduction measures can reduce losses, compensations and governmental debt and stabilize the economic growth of the region and the wealth of individuals.

Catastrophe losses are shared by many participants, such as individuals (cells), governments, insurers, reinsurers, and investors. In the model we call them “agents” as the main balance equations of our model are similar for all of them. For each agent i a variable of concern is the wealth W_i^t at time $t = \overline{0,T}$

$$W_i^{t+1}(\omega) = W_i^t(x,\omega) + I_i^t(x,\omega) - O_i^t(x,\omega), \quad i = \overline{1,n}, \; t = \overline{0,T-1}, \; \omega \in \Omega, \qquad (1)$$

where W_i^0 is the initial wealth. This is a rather general process of accumulation that, depending on the interpretation, describes the accumulation of reserve funds, the dynamics of contamination, or the processes of economic growth with random disturbances (shocks), the reserves of the insurance company at moment t, the gross national product of a country or the accumulated wealth of a specific region. In more general cases, when catastrophes may have profound effects on economic growth (can “move” the economy, see, for example, Nordhaus, 1993; Manne and Richels, 1992), this model can be generalized to an appropriate version of an economic-demographic model (MacKellar and Ermolieva, 1999) that enables to represent the movements of individuals and the capital accumulation processes within the economy.

We use the same index i for quite different agents. Therefore, the variables $I_i^t(x,\omega)$, $O_i^t(x,\omega)$ may have quite different meanings. For example, for each insurer i we can think of I_i^t as premiums π_i^t which are ex-ante arranged and do not depend on ω, whereas O_i^t is defined by the claim size S_i^t and possible transaction costs, which triggers a random jump of the risk reserve W_i^t downwards at random times of catastrophic events (as in the simple model described in Section 2). If i corresponds to a cell, then income I_i^t may be affected by a catastrophic event ω generated by a catastrophe model. The incomes I_i^t can be defined by a set of scenarios or through a regional growth model with a geographically explicit distribution of capital among the cells. The term O_i^t may include losses L_i^t, taxes and premiums paid by i. For the central or local governmental agent i (e.g., mandatory insurance, catastrophe fund) I_i^t may include a portion of taxes collected by the government (compensations of losses by the government), and O_i^t may consist of mitigation costs, debts, loans and fees paid for ex-ante contingent credits.

For each i consider a stopping time τ_i for process $W_i^t(x,\omega)$, i.e., a random variable with integer values $t = \overline{0,T}$. The event $\{\omega : \tau_i = t\}$ with fixed t corresponds to the decision to stop process $W_i^t(x,\omega)$ after time t. Examples of τ_i may be $\tau_i = T$, the time of the first catastrophe, or the time of the ruin before a given time $T : \tau_i(x,\omega) = \min\{T, \min[t : W_i^t(x,\omega) < 0, t > 0]\}$. The last example defines τ_i as a rather complex implicit function of x.

Assume that each agent i maximizes (possibly negative) “wealth” at $t = \tau_i$. The notion of wealth at t requires an exact definition, as it must represent in a sense the whole probability distribution of W_i^t. The traditional expected value EW_i^t may not be appropriate for the probability distributions of W_i^t affected by rare catastrophes with high consequences. As a result, they may have a multimode structure with “heavy tails”. We can think of a maximal value V_i^t, which does not overestimate, in a sense, the random value W_i^t, i.e., cases when $\min_{s \le t}\left(W_i^t(q,\omega) - V_i^t\right) < 0$. Formally, V_i^t can be chosen by maximizing:

$$V + \gamma E \min\{0, W_i^t(x,\omega) - V\}, \tag{2}$$

or the more general function $V - \gamma E d\left(W_i^t(x,\omega) - V\right)$, for some function $d(\cdot) \ge 0$, $0 < \gamma < 1$, where the second term can be considered as the risk of overestimating wealth $W_i^s(x,\omega)$ for $s = 0,1,\ldots,t$. Let us note that the concept of equation (2) corresponds to the well-known Conditional Value at Risk (CvaR) risk measure (see Artzner *et al.*, 1999; Jobst and Zenios, 2001; Rockafellar and Uryasev, 2000). For the normal distribution and $\gamma = 1/2$, the value V_i^t maximizing equation (2) coincides with the traditional mean value EW_i^t. It is easy to see that with a quadratic function $d(\cdot)$ we can also achieve the mean-variance efficiency as in Markowitz (1987). Besides the maximization of wealth, the agent i is concerned with the risk of insolvency, i.e., when $W_i^s < 0$ for some $s = 0,1,...,t$ as well as the lack of sustained growth, i.e., when $I_i^s - O_i^s < 0$ for some $s = 0,1,...,t$. In accordance with this, consider the stochastic goal functions:

$$f_i^t(x,V,\omega) = V_i^t + \gamma_i \min\left\{0, \min_{s\in T_t^1}\left[W_i^s(x,\omega) - V_i^s\right]\right\} + \delta_i \min\left\{0, \min_{s\in T_t^3} W_i^s(x,\omega)\right\} +$$
$$+ \beta_i \min\left\{0, \min_{s\in T_t^2}\left[I_i^s(x,\omega) - O_i^s(x,\omega)\right]\right\}$$

$$F_i\ (x,V) = Ef_i^{\tau_i(x,\omega)}(x,V,\omega), \qquad (3)$$

where T_t^k, $k = 1,2,3$, is a subset of time moments in interval $[0,t]$, e.g., all points, $T_\tau = t$ or some other "critical" moments; non negative γ_i , δ_i , and β_i are substitution coefficients between wealth V_i^t and risks of overestimating wealth, insolvency, and overestimating sustained growth. All these requirements reflect survival and stability constraints of agents. Let us notice that in equation (3) we use a significantly modified form of equation (2), which seems to be more appropriate for dynamic problems involving catastrophic risks. The operation min with respect to $s \le t$ orients towards the extremal in time values. Each agent attempts to maximize $F_i\ (x,V)$.

Pareto optimal improvements of risk situations with respect to goal functions $F_i(x,V)$ of different agents can be achieved by maximizing:

$$W(x,V) = \sum_{i=1}^{n} \alpha_i F_i(x,V) \qquad (4)$$

for different weights $\alpha_i \ge 0$, $\sum_{i=1}^{n} \alpha_i = 1$. These weights reflect the importance of the agents. The maximization of $W(x,V)$ for different weights α_i, $i = \overline{1,n}$, corresponds to a stochastic version of the welfare analysis (Ginsburg and Keyzer, 1997). The minimization of the function in equation (4) is a stochastic maximin problem (see Ermoliev and Wets, 1988). The resulting optimal strategy takes into account the goals of quite different agents, in particular, their goals to increase welfare, decrease risks of insolvency, and improve stability of growth. It also takes into account different ex-ante and ex-post decisions. In this sense, we say the optimal strategy is to be robust. Detailed analysis of the model can be found in Ermolieva *et al*., (1997, 2000). Let us discuss its applications in some case studies.

5 Case Studies: Catastrophic Risk Management

The adequacy of the methodology was tested in a number of case studies. In its first application, the integrated model analyzed the insurability of risks in the Irkutsk region in Russia, which is exposed to the risks of earthquakes (Amendola *et al*., 2000a). The results demonstrated the model's capability of generating insurance strategies that are robust with respect to dependencies and uncertainties induced by the catastrophes, thus reducing the risk of bankruptcy to the insurers.

In the second case study (Ermolieva *et al*., 2000), the integrated model was customized for catastrophic flood management, in which case it consisted of a catastrophe model and a Multi-Agent Economic Model (MAAS). The "River" module of the catastrophe model calculated the volume of discharged water into the pilot region from different river sections for given land-use practices, heights of dikes, scenarios of their failures or removals, precipitation patterns, while the spatial GIS-based Inundation module mapped water released from the river into levels of standing water and thus it can estimate the area of the region affected by the flood. The direct economic losses were calculated in a "Vulnerability" module. This module could, in principle, incorporate possible cascading effects, such as floods causing unavailability of lifeline systems and its consequences. It also included loss reduction measures thereby increasing the sustainability of the region towards floods, e.g., changes in land-use, flood preparedness measures, etc. Further, the MAAS module enabled the calculation of economic losses and gains for different agents, such as individuals, local governments, mandatory or voluntary catastrophic insurance, central government, and investors. Integrated all together, the models resulted in a framework that was capable of transforming spatial probabilistic scenarios of rains, dike failures, risk reduction measures and risk spreading schemes into histograms (probability distributions) of gains and losses, and underpayments and overpayments of agents.

The case study for a seismic-prone Italian region presented here illustrates the fact that neither the market nor the government may be considered as the efficient mechanism for catastrophic risk management. Only some form of a public-private partnership would be appropriate (Kunreuther and Roth, 1998).

Many governments are pursuing policies to reduce their role in compensating victims. Nevertheless, a study by Linnerooth-Bayer and Amendola (2000) confirms that the victims and their governments bear the major losses from natural disasters and, worldwide, there is only moderate risk transfer with insurance. An important consideration for national insurance strategies is linking private insurance with mitigation measures to reduce losses. Insurers, however, are reluctant to enter markets that expose them to the risk of bankruptcy. In the USA, for example, many insurers pulled out of catastrophic risk markets in response to their large losses from natural catastrophes in the last decade (ISO, 1994).

In Italy, a law for integrating insurance in the overall risk management process was proposed only in late 1997 (within the Design of Law 2793: "Measures for the Stabilization of Public Finance"). This opened a debate, which has not yet been concluded by a legislative act. Therefore, policy options for a national insurance strategy are still open to investigation.

In these studies, we incorporated the data provided by the Institute for Research on Seismic Risk (Petrini, 1995) into a Monte Carlo earthquake generator, which was created (see Amendola *et al*., 2000a, b; Baranov *et al*., 2002; Ermoliev *et al*., 2000a, b; Rozenberg *et al*., 2001) using Gütenberg–Richter law and the attenuation characteristics of the region (see Figure 3). The generator, in fact, can be easily adapted to incorporate different kinds of distributions, non-poissonian catastrophic processes, as well as micro zoning within a municipality.

The Tuscany region was subdivided into M ≈ 300 sub-regions, which corresponded to the number of its municipalities. For each municipality j the number and types of buildings, their vulnerability, and number of built cubic meters represented the so-called estimate of "wealth" W_j. Simulated in time and space, earthquakes $\omega_0, ..., \omega_t$ occurred at different municipalities, inside or outside the region, had random magnitudes and, therefore, affected a random number of municipalities.

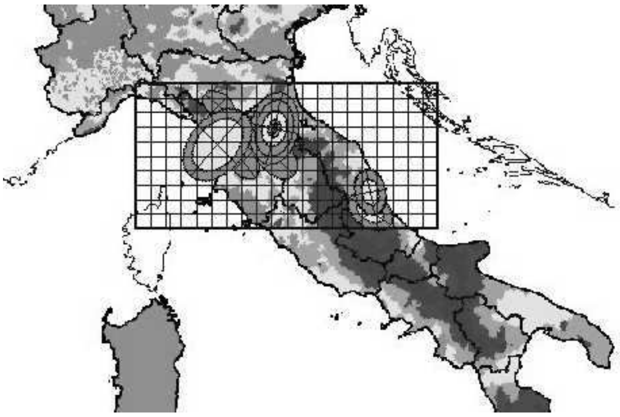

Figure 3: Earthquake generator.

The economic losses of destroyed cubic meters of a building were defined as the cost for their reconstruction. Obviously, the reinforcement of a building's environment would reduce the losses. This fact was adequately reflected in the model, which allowed to study the interplay between mitigation measures and risk-sharing mechanisms (insurance, reinsurance, financial markets). The concern of this study was the following. In its early version, the 1998 Italian Design of Law 2793 to reduce the impact of natural disasters on the governmental budget included in its Article 31bis provisions for an insurance program against all natural hazards (Amendola *et al.*, 2000b). It was not intended to make this insurance mandatory, but to make mandatory the extension of a fire insurance policy for all natural hazards. In addition to tax incentives for such an insurance, it stipulated a maximum exclusion layer of 25%, the creation of a pool of insurance companies with an appropriate reserve fund, e.g., corresponding to the annual average government payment for compensating losses (with some forms of state guarantee to be specified further), and linking the premium to that for fire policy. This article was withdrawn, and later proposals are still the subject of discussion.

Starting from these principles, the model analyzed various policies that were suggested by stakeholders. It also offered optimal and sustained solutions in the sense of indicators that were defined in Section 4. We assumed that an insurance company (this might be a pool of companies or the government itself acting as an insurer) covered a fraction q, e.g., q = 0.75 of earthquake losses. The rest, $\nu = 1 - q$ according to the Design of Law, was compensated by the state. Thus, in the case of excessive losses the state could be severely affected.

The policy options proposed were, for example, on insurance premiums. Standard actuarial approaches calculate the premiums based on the expected losses. The proposed options followed similar principles. In the outlined numerical experiments we consider the following three rules:

1. Premiums based on the average damage over all of the municipalities (solidarity principle, bringing less exposed locations to pay premiums equal to those more severely exposed, as in the spirit of the proposed insurance program).

2. Location-specific premiums based on average damage in the particular municipality, i.e., risk-based premiums.

However, the use of average losses may be misleading in the case of heavy tailed distributions that are typical for catastrophic losses. The stochastic optimization risk management model outlined in Section 4 allows the calculation of premiums taking into account sustainability indicators of insurers and the state, constraints on individual incomes, willingness to overpay premiums, etc. These model-based robust premiums were implied as the third policy option:

3. Premiums that fairly equalize the risk of instability for the insurance company (the insurer may become bankrupt only once in 1000 years) and the risk of premium overpayment for exposed municipalities (municipalities overpay premiums only once in 100 years).

Besides premiums, we also analyzed policy options on location specific coverages and the amount of governmental compensation.

Figures 4–7 illustrate some numerical results. They show considerable differences between Options 1, 2 and Option 3. The number of simulations is shown on the vertical axis.

For *Option 1*, where the burden of losses is equally distributed over the population, the simulation of catastrophic losses showed that the annual premium is equal to the flat rate of 0.02 monetary units (m. u.) per cubic meter of building.

For *Option 2,* Figure 4 shows the distribution of municipality-specific premiums based on average damage in each municipality (or according to the municipality-specific risk). There is a prevailing number of municipalities (about 220) that have to pay 0.02–0.03 m. u., which is close to the flat rate of 0.02, as in Option 1. About 20 municipalities are at no risk at all (0 rate). Municipalities that are more exposed to risk have to pay 0.04 and higher rates (more than 50 municipalities).

Figure 6 shows the distribution of the insurers' reserve (cumulated at τ within 50 years) at Options 1, 2 premiums. The volume of capital is shown on the horizontal axis. The probability of insolvency (when the risk reserve accumulated up to the catastrophe is not enough to compensate incurred losses) is indicated on the right-hand ordinate axis. There is a rather high probability of 'small' insolvency (values -90, -40 occurred 190 and 90 times out of 500 fast simulations). High solvency (more than 500 m. u.) occurred in about 10 per cent of the simulations. The size of insolvency would represent the cost to the government to cover the losses uncovered by the pool. Another option may be to transfer a fraction of the losses to international financial markets, as analyzed in Ermolieva *et al.*, 2000.

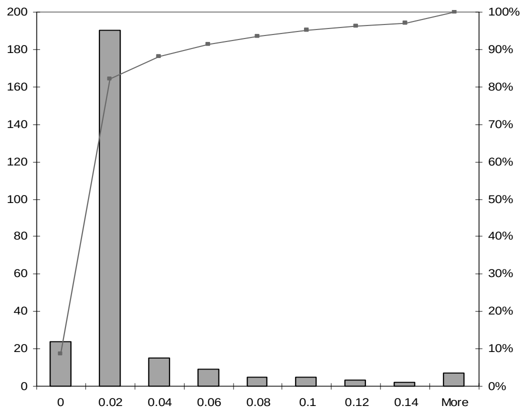

Figure 4: Distribution of municipality-specific premiums (per m^3 building volume/municipality, in % terms).

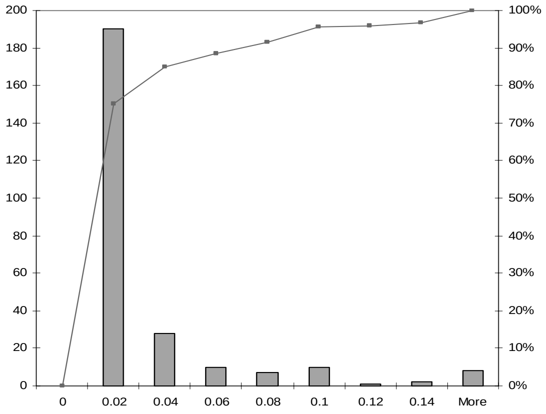

Figure 5: Distribution of "fair" premiums, *Option 3*, (per m^3 building volume/municipality, in % terms).

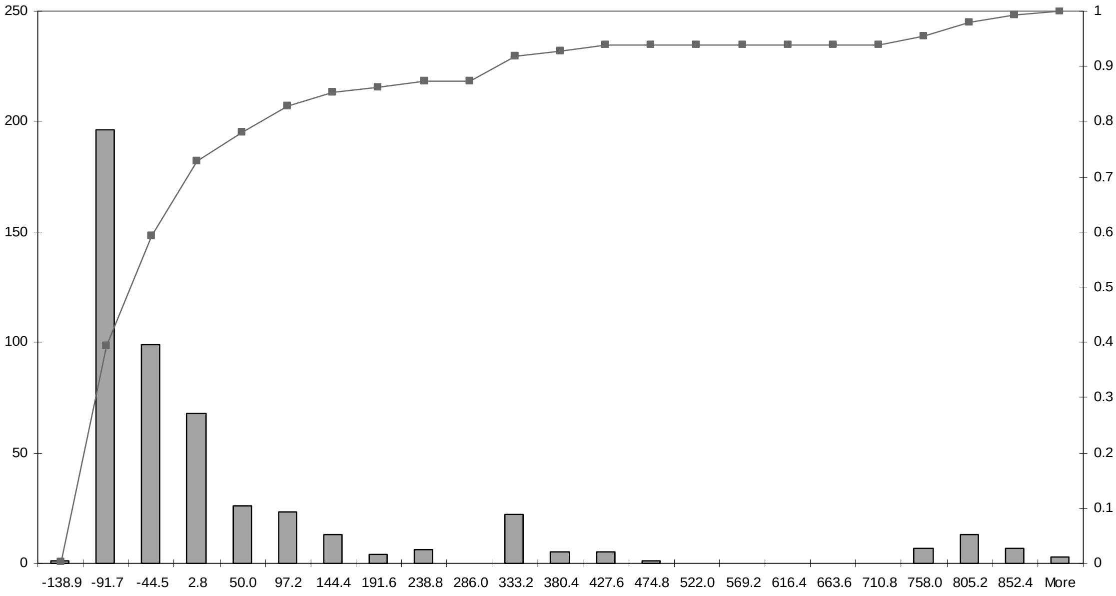

Figure 6: Distribution of insurer's reserve, Options 1, 2 (thousands m. u., 50 years).

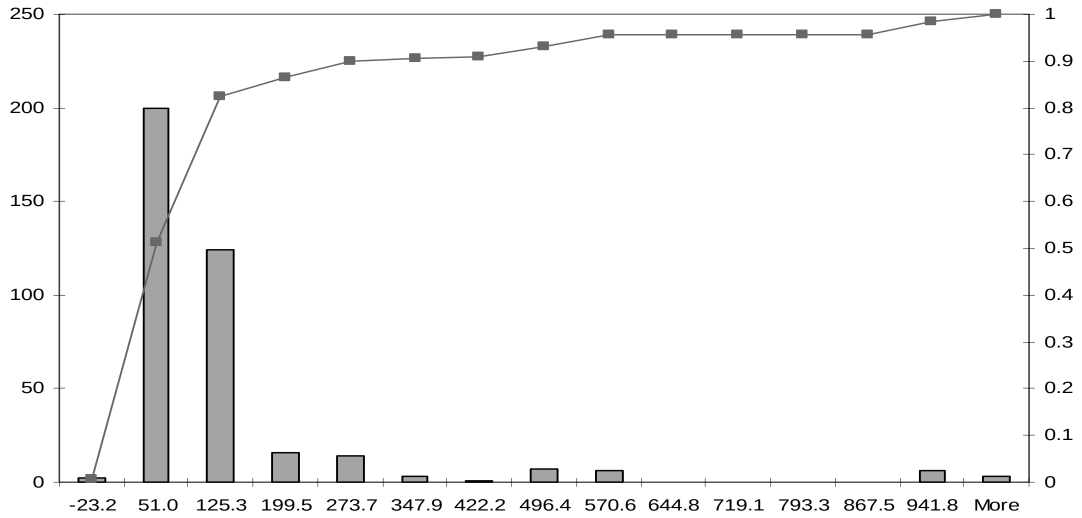

Figure 7: Distribution of insurers' reserve, Option 3 (monetary thousands, over 50 years).

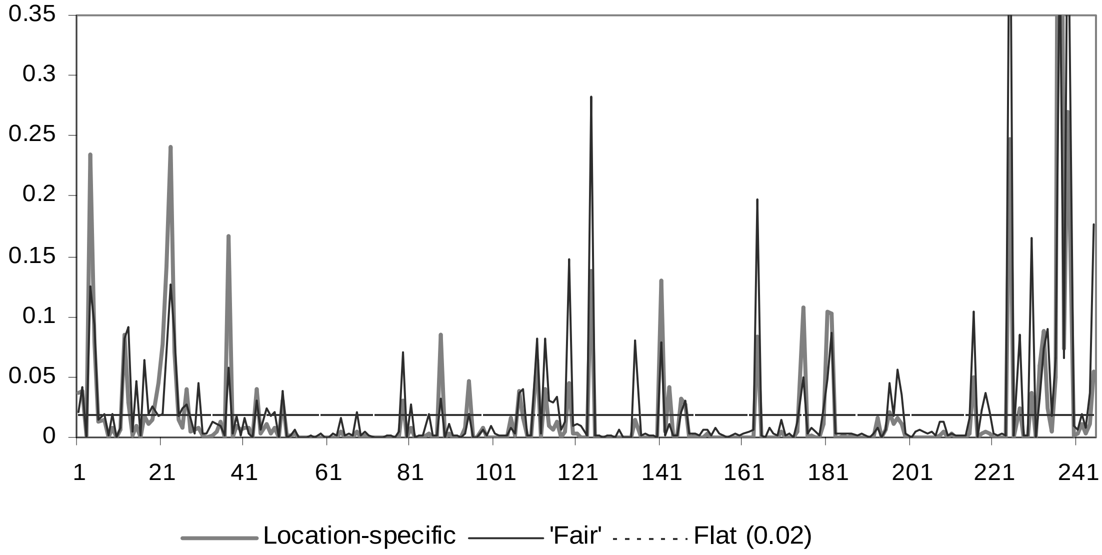

Figure 8: Comparison of Options: municipality-specific, "fair" and flat (0.02) premiums.

Figure 5 shows the distribution of premiums for *Option 3*. According to this principle, most of the municipalities (190) have to pay close to the flat rate of 0.02–0.03 m. u. per cubic meter of a building. Rates of 0.04 and higher have to be paid by about 100 municipalities. In this case, the highest premium rate is 0.5, which is much lower when compared to the highest rate of 1.2 of Option 2. The distribution of the insurer's reserve in Figure 7 also indicates the improvement of the insurer's stability — the frequency of insolvency is considerably reduced.

Figure 8 is very illustrative. For each municipality, it shows the optional premiums to be paid — the flat premium rate of 0.02, the Option 2 municipality-specific rate, and the 'fair' premium of Option 3. Many municipalities in all three options have to pay the premium rate, which is about the flat rate (0.015–0.03). For quite a number of municipalities in Options 2, the rate significantly exceeds the flat rate. For these municipalities, special attention should be given as to whether they are able to pay such high premiums. Option 3 allows taking such individual constraints on overpayments into account and working out the efficient premiums both for the insurer and the municipalities.

6 Pertinence of Integrated Disaster Management Models for Analyzing Climate Change

Managing the risk of climate change can be regarded as a special type of integrated disaster management. Although technically the same phasing of the disaster cycle applies — mitigation/prevention, preparedness, response and recovery — the sheer scale over time, geography and scope together with a different political/economic setting, makes risk management of climate change a different beast. Therefore, regulatory approaches, be it endogenously generated or externally enforced, to climate change are especially prone to failure. Michaelson (1998) presents three main reasons for failure due to deficiencies in current regulatory policy practice:

- Global warming is an absent problem, and thus deniable and discounted. In the absence of tangible evidence, it is politically tenable to do nothing, especially in light of uncertainty regarding how much and what type of action is required.

- Global warming is a difficult problem to solve — it is costly, unevenly distributed, complex, debatable in scope, and ill matched to our policymaking apparatus. A great deal of motivation is needed, therefore, to achieve any meaningful progress.

- Global warming presents a tragedy of the commons, so that even if international actors were prepared and competent to act, they would have a structural disincentive to do so.

In addition, as mentioned at the beginning of this paper, the character of climate change has historically been characterized by large-scale abrupt climate changes due to a powerful feedback mechanism within a tremendously complex climate system. These abrupt climate changes occurred even without such dramatic changes of the climate system such as the current changes of atmospheric greenhouse gas concentrations.

These are unprecedented challenges to scientists, practitioners, agencies and policy makers involved in the management of climate risks. A precondition for a robust regulatory framework is sound decision theory that reflects the above-mentioned challenges. We conclude that the class of models presented in this paper appears to be suitable. Let us discuss a number of features of the climate change problem and its associated social dilemma that so far have not been well analyzed in integrated assessments, which we will be able to tackle, however, with the help of the models presented in this paper.

As mentioned in the introduction, abrupt climate change is a field that is still largely under-explored by the integrated assessment community. Technically, abrupt climate change occurs when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than its causes. The complex processes in the climate system may allow the cause of such an abrupt climate change to be undetectably small (NRC, 2002). This leads to a situation where extreme events of the climate system, its associated risks and mutual dependency of extremal values, can only be assessed imperfectly. Ignorance arises from the very nature of the complex climate system per se and its interaction with socioeconomic systems. In this paper, we have illustrated that it is possible to account for extreme events and the ambiguities. In particular, the notion of developing robust strategies in an environment of uncertain risk appears to be a valuable concept for analysis.

Another serious problem arises from the granularity of hazard and vulnerability in space and time. Due to correlation, be it linear or non-linear, between individually non-catastrophic risks the ensemble may bear the potential for a catastrophe. Extreme events, like flooding or a storm, can be handled as single events. However, the globalized and increasingly integrated economy of today gives risk to powerful and many times hidden feedback mechanisms. An interesting case is that of the crisis of the reinsurance industry. Throughout most of the 90s, when stock markets were riding high and insurance claims were manageable, business focus was much on enlarging market share leading to fierce competition. Unrealistic expectations about the Information Technology (IT)-based wonder economy lead to a situation where shrinking premium income was not offset by investment gains. Apart from the irony that earnings from the fossil fuel biased investment portfolio (another correlated risk) were very high, increased competition lead to situations where insurance companies had to repeatedly dip into their reserves. Then, at the end of the 90s when trust in sustained economic growth began fade away and the industry had to pick up the 9.11 event and the relatively mild flood losses in Europe, large losses had to be announced by the reinsurance industry. Thus, the combined effect of falling stock markets, partly triggered or reinforced by insured catastrophes, unrealistic premiums and underwriting practices due to wrong investment expectations and temporal clustering of independent calamities, can wipe out much of the industry’s capital, leading to questionable robustness of the entire industry downstream and its customers. Spatial and temporal dependencies of risks have successfully been treated in the case studies presented in this paper and technically it should also be feasible to do within the integrated models of climate change.

There is not only a great deal of ignorance about risk exposure due to climate change, but risk is also not independent from our decisions. Climate risk is endogenously managed by human response, be it ex-ante or ex-post. As discussed, the responses are mitigation and adaptation measures, where mitigation measures can be more associated with hazard reduction and adaptation measures are aimed more at vulnerability management. Risk mitigating and risk containing actions are induced by society's reaction vis-à-vis the risks it endogenously co-creates. Despite this simple insight, integrated models of climate risk management still do not deal with the endogeneity problem. On the other hand, in this paper we have shown that the risks can be endogenized, which, however, leads to methodologically very demanding model structures. We are convinced that integrated models of climate change can only be used as an useful “mitigation measure” if risks are treated fully endogenously.

Most of the integrated assessment work on climate change has focused on the technical details of mitigation and adaptation strategies. It must be recognized that global climate change will, in all probability, have tremendous long-term social consequences and, therefore, new strategies for societal planning, governance and management have to be developed. Models that facilitate stakeholder consultation in an effective way are highly desirable. The types of models presented here are capable of representing a variety of stakeholder groups in an agent-based setting. Using appropriate catastrophic risk management models and methods allows us to analyze various ex-ante burden-sharing arrangements while paying attention to all measures of the disaster cycle (mitigation, preparedness, response, recovery) and assign responsibilities as well as analyze trade offs in close cooperation with stakeholders.

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