PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2006) **364**, 2147–2165
doi:10.1098/rsta.2006.1818
Published online 28 June 2006

Natural disasters and the challenge of extreme events: risk management from an insurance perspective

By Anselm Smolka*

Head of Department, Geophysical and Hydrological Risks, Munich Reinsurance Company, Königinstrasse 10, 80791 Munich, Germany

Loss statistics for natural disasters demonstrate, also after correction for inflation, a dramatic increase of the loss burden since 1950. This increase is driven by a concentration of population and values in urban areas, the development of highly exposed coastal and valley regions, the complexity of modern societies and technologies and probably, also by the beginning consequences of global warming. This process will continue unless remedial action will be taken. Managing the risk from natural disasters starts with identification of the hazards. The next step is the evaluation of the risk, where risk is a function of hazard, exposed values or human lives and the vulnerability of the exposed objects. Probabilistic computer models have been developed for the proper assessment of risks since the late 1980s. The final steps are controlling and financing future losses. Natural disaster insurance plays a key role in this context, but also private parties and governments have to share a part of the risk. A main responsibility of governments is to formulate regulations for building construction and land use. The insurance sector and the state have to act together in order to create incentives for building and business owners to take loss prevention measures. A further challenge for the insurance sector is to transfer a portion of the risk to the capital markets, and to serve better the needs of the poor. Catastrophe bonds and microinsurance are the answer to such challenges. The mechanisms described above have been developed to cope with well-known disasters like earthquakes, windstorms and floods. They can be applied, in principle, also to less well investigated and less frequent extreme disasters: submarine slides, great volcanic eruptions, meteorite impacts and tsunamis which may arise from all these hazards. But there is an urgent need to improve the state of knowledge on these more exotic hazards in order to reduce the high uncertainty in actual risk evaluation to an acceptable level. Due to the rarity of such extreme events, specific risk prevention measures are hardly justified with exception of attempts to divert earth-orbit crossing meteorites from their dangerous path. For the industry it is particularly important to achieve full transparency as regards covered and non-covered risks and to define in a systematic manner the limits of insurability for super-disasters.

Keywords: natural disasters; extreme events; risk management; risk financing; insurance

*asmolka@munichre.com

One contribution of 20 to a Discussion Meeting Issue ‘Extreme natural hazards’.

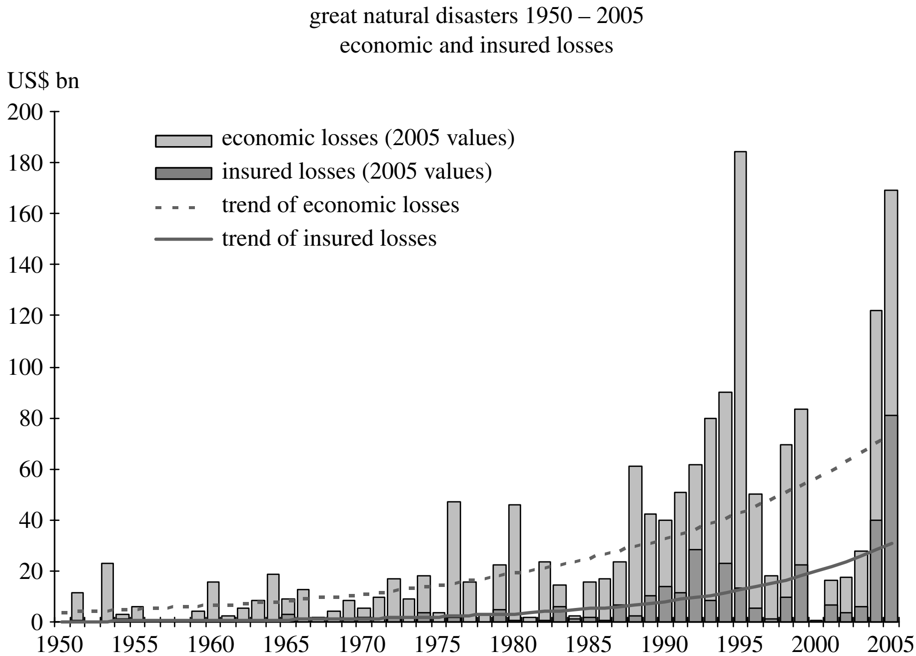

Figure 1. Losses from great natural disasters (far exceeding 100 deaths or US$ 100 m in losses), 1950–2005. Figures are adjusted for inflation.

1. Growing losses: need for action

The loss data on great natural disasters since 1950 show a dramatic increase in catastrophe losses over the last few decades. Actual loss figures and trend curves are shown in figure 1. The reasons for this development are manifold and encompass the increase in world population and exposed values, their concentration in large conurbations, social and economic factors as the development of highly exposed regions and the high vulnerability of modern societies and technologies, and eventually changes in the natural environment, e.g. global warming and the related effects on regional climate.

As the underlying factors for the observed loss trend remain unchanged, a further increase in losses from natural disasters is inevitable. The development of coastal areas for residential, commercial and industrial use is just one phenomenon that exemplifies this trend, as demonstrated by the staggering losses produced by the South Asian tsunami of 26 December 2004, and Hurricanes Katrina and Wilma affecting the US Gulf Coast, Florida and Yucatán/Mexico in 2005. Hurricane Katrina also illustrated the potential worldwide implications of natural disasters by the severe shortage in oil-producing and refining capacities and the ensuing sharp price increases in the global oil market.

2. Risk management in the context of natural disasters

Coping with future loss burdens represents a formidable challenge to the insurance industry and requires a holistic approach to risk management. Such an approach comprises the steps of risk identification, risk evaluation, risk control and risk financing.

From an insurance perspective risk consists of three components: the hazard, the vulnerability of objects exposed to a hazard and the value of the exposed objects. The hazard is usually defined as the exceedance probability of an event of a specified minimum size, e.g. the wind velocity in the case of windstorms or the ground shaking in the case of earthquakes. The vulnerability is expressed as the expected average loss as a percentage of the replacement value and depends on the hazard. For disaster prevention, planning and response in general this financial definition of vulnerability should be supplemented by loss of life.

(a) *Risk identification*

Munich Re recognized in the early 1970s the growing importance of natural disasters for the insurance industry. This was a consequence of great natural disasters that occurred in less developed regions and had an unexpected impact on the international reinsurance market. Examples include the earthquake in Managua/Nicaragua in 1972 (US$ 80 million insured loss) and the tropical cyclone Tracy in Darwin/Australia in 1974 (US$ 250 million insured loss). Therefore, the Geo Risks Research Group was founded in 1974. It now employs about 20 geoscientists from different disciplines. For the purposes of risk identification, a global natural disaster database (Munich Reinsurance Company 2003, 2005) was developed. Another successful product was the World Map of Natural Hazards, first published in 1979 and now in its third edition (Munich Reinsurance Company 1998), and also available on a CD-ROM. The World Map marks the transition to risk evaluation in the sense that it describes probabilities for one component of risk, which is the hazard, see figure 2.

(b) *Risk evaluation*

The first fully probabilistic earthquake risk model, that allowed the calculation of average annual losses (AALs or net rates) and probable maximum losses (PMLs), was developed in 1987. The use of such risk models has since become commonplace in the insurance industry. In such models, data on the hazard (e.g. earthquake intensities, wind speeds or flood heights and their respective distribution in space and time), on the exposed objects (their distribution per site and construction type and/or type of use) and on their vulnerabilities are combined and evaluated. The outcome of this procedure is a stochastic event set that describes the full probability distribution of potential event losses in the investigated region. Figure 3 shows schematically how such models work.

Figure 4 is the graphical presentation of the calculation result called a loss exceedance curve. The example shows that a loss of 2.4% (or higher) of the total values in the considered region has to be expected on average once in 100 years and a loss of 6.5% once in 1000 years. In insurance parlance, such a single value is called PML. Probable maximum losses form the basis for measures to guarantee the financial stability of a company by means of reinsurance protection and limitations of coverage. The other important application of such risk models is the calculation of an adequate rate, i.e. the net insurance rate that would be

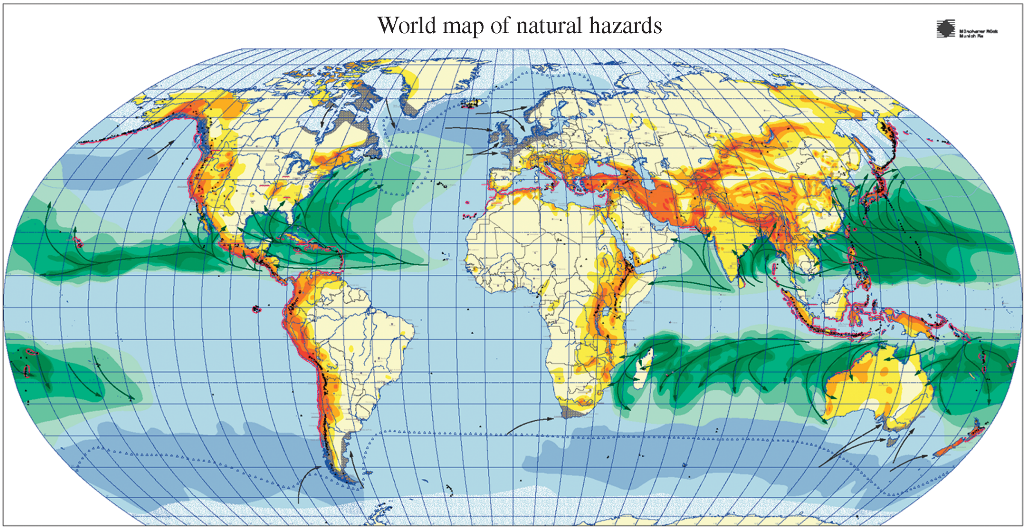

Figure 2. World Map of Natural Hazards. Earthquake hazard is shown in yellow–brownish colours and has been classified into five grades according to the minimum intensity (Modified Mercalli scale) to be reached or exceeded once in 475 years. Darkest colour means highest hazard. The hazard of tropical windstorms is presented in green colours, again darkest colour corresponds to highest hazard. Classification is according to the five degree Saffir–Simpson scale. Green arrows represent the main cyclone tracks. Other hazards shown are extratropical storms (grey shading) and active volcanoes (small black symbols).

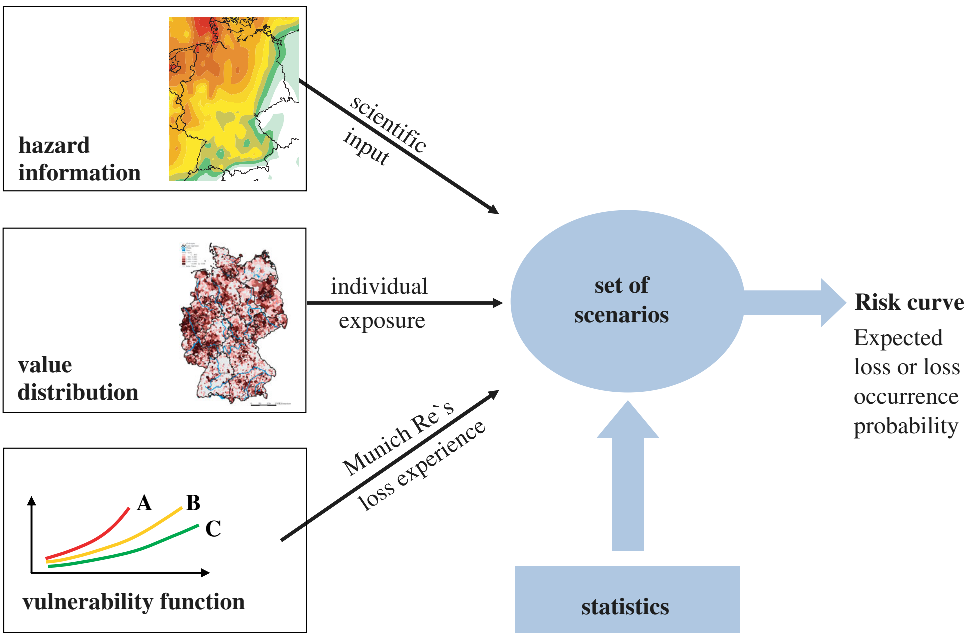

Figure 3. The Munich Re risk model MRHazard. Data on hazard, exposed values and vulnerability are combined probabilistically. This results in an event set which serves as the basis for calculating insurance rates and probable maximum losses.

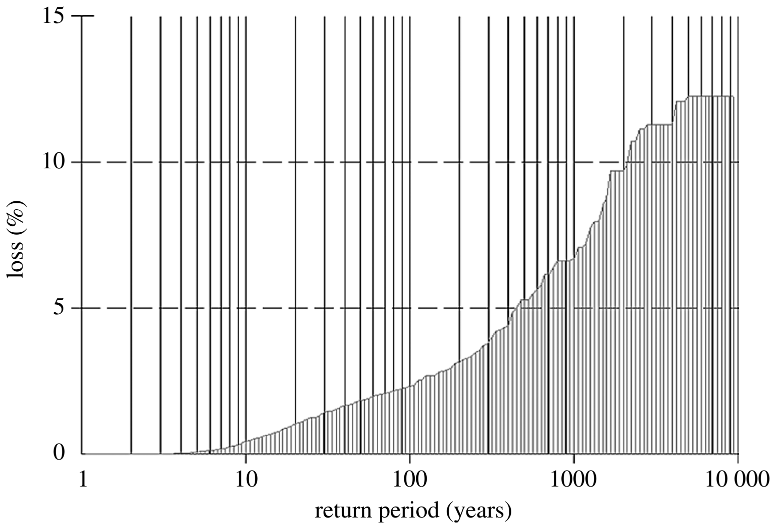

Figure 4. MRHazard—example for a PML (or loss exceedance) curve. The PML curve is the graphical representation of the event set produced by MRHazard. It shows the losses to be expected as a function of annual occurrence probability or its inverse, that is the recurrence period (in years). The curve in the graph is an example for a sample portfolio in Japan and tells that a loss of about 2.3% (or higher) of exposed values all over the country would have to be expected once in 100 years, and a loss of 6.5% once in 1000 years.

necessary to compensate for all possible losses over time. This is the average annual loss AAL. In mathematical diction, this is the integral over the full probability distribution.

(*c*) *Risk control*

The next step after identifying and evaluating the risks is risk control. The insurance industry has various measures at its disposal to keep its risk within affordable limits. They are briefly introduced below:

- (i) calculation and application of a risk-adequate price (i.e. the net insurance rate),
- (ii) accumulation control, i.e. monitoring the insured liabilities within a country or region,
- (iii) self-participation of the insured party in the loss, in the form of deductibles that reduce the number and amount of small insurance claims in the event of large disasters,
- (iv) liability limits, that reduce the exposure from very large insurance claims from the top (i.e. losses are compensated only up to the limit),
- (v) exclusion of particularly exposed areas or certain hazards. An example would be regions that are frequently flooded and therefore do not fulfil one of the principal preconditions of insurability, that is the lack of foreseeability of an event,
- (vi) improved claims settlement, that requires the formulation of contingency plans for regulating sometimes hundreds of thousands or even millions of

claims in one single disaster as observed in the Northridge (Los Angeles) earthquake of 1994, the European windstorms of 1999 or Hurricane Katrina in 2005,

(vii) reinsurance and retrocession. Whereas the aforementioned measures work on the level of the original insurance policy, reinsurance and retrocession (i.e. the equivalent of reinsurance for the reinsurance sector itself) serve to limit the exposure from the large number of claims to be expected in great natural disasters by means of reinsurance contracts,

(viii) catastrophe reserves. Premiums from natural disaster insurance cannot be considered as 'earned' premiums after 1 year. Great disasters happen rarely, and therefore the relevant premiums have to be set aside for forming financial reserves that are then tapped when the event occurs, and

(ix) loss prevention. The trend to dramatically growing losses (see figure 1) shows that it is essential to strengthen the efforts in loss prevention and mitigation, i.e. taking proactive measures to reduce losses from future disasters by means of land-use planning, construction techniques and contingency plans.

How such measures are implemented, and by whom, is the subject of the following section.

(*d*) *Risk financing: the principle of risk partnership*

Coping with future loss burdens represents a formidable challenge that requires the cooperation of all parties involved, i.e. the potentially affected private persons and industries, the financial sector and the state. Within the context of the role of insurance in disaster relief, we can distinguish between the insured persons or entities, primary insurers, reinsurers, capital markets and governments/public authorities.

Each of these parties has its own tasks and responsibilities in managing the risk arising from natural disasters. Beyond the pure financing of future losses much more effort than hitherto needs to be invested in a pro-active strategy, i.e. in reducing and preventing future losses. Such a strategy is not just a matter of financial resources. Good and advanced planning and coordination at all levels, from households and industrial companies to public institutions and authorities is necessary. What precisely are the tasks of these parties?

Householders and business owners (the insureds) can do a lot in order to reduce the risk to their property by proper maintenance and securing sensitive items like equipment, electronic installations and machinery. In industrial businesses emergency planning can help to prevent or minimize losses from future disasters. Finally, some of the financial risk has to be borne by the insureds in order to keep the interest in loss reduction awake. Typical forms of self-participation are deductibles, preferably expressed as a percentage of the sum insured, and co-insurance, i.e. a percentage participation in each and every loss.

Primary insurers have to provide and secure capacity by: charging technically adequate rates (i.e. rates that suffice to cover the expected future net losses); applying appropriate underwriting guidelines; accumulation control and portfolio management; establishing reserves for natural perils; and limiting their liability according to their financial strength $\Rightarrow$ reinsurance protection.

Reinsurers are often the main risk carriers in natural disaster losses, making proper risk management all the more a primary task that includes: balancing the risk over time and regions; providing technical support to the clients in rating considerations and assessments of PMLs; and controlling and limiting liabilities (setting cession/occurrence limits, budgeting, retrocession; cession limits are based on sums insured, occurrence limits on losses).

Capital markets came onto the scene only a few years ago. This type of alternative risk transfer (ART) must be seen as a supplement to reinsurance rather than competition. The principle behind ART is to transfer (financial) catastrophe risk into the capital markets instead of taking out traditional reinsurance. The main function is to provide additional capacity for top-rank, very large losses. Typical ART products are so-called catastrophe bonds (known as cat bonds), swaps and derivatives. In popular terms, a cat bond means betting against the occurrence of a disaster within a specified timeframe. Swaps involve an exchange of risks from specified disasters between two companies, e.g. earthquake in Tokyo against windstorm in Europe. Derivatives are commonly used for weather related risks, e.g. average temperature or precipitation falling below (or exceeding) a specific threshold level that would imply a financial loss to a business owner.

In the insurance context, the state has to act as a reinsurer of last resort for very rare, extraordinary losses and/or uninsurable risks that exceed the capacity of the private sector. The main task of the state lies, however, in the field of risk management and risk reduction and involves: designing and enforcing land use and building regulations; securing the serviceability of critical facilities and infrastructure; developing emergency plans that define precisely the responsibilities and the coordination of the authorities involved; and granting tax exemption for private insurers' catastrophe reserves.

Within this context, the role of the insurance sector is well-established. The capital markets, on the other hand, still have to prove that they are willing to provide reliable and continuous capacity when investors have lost their money after large disasters. Furthermore, almost the entirety of ART programmes have so far been placed for highly developed countries. Complexity of the programmes and the connected costs, as well as investor attitudes requires usually mature insurance markets. The state should create an environment in that the greatest possible use is made of private resources for disaster recovery, combined with the availability of protection for as many people as possible. Linking the availability of such protection to the observance of building regulations can provide an efficient mechanism for code enforcement, especially where new constructions are concerned. Notwithstanding, mechanisms aiming at code compliance may serve to encourage rehabilitation measures as well. Another important role in the 'mitigation cycle' could be, and increasingly is, played by mortgage banks requiring natural disaster insurance as a precondition of the loan.

(*e*) *Disaster insurance: a tool for risk mitigation?*

The use of disaster insurance as a motivating tool within the framework of loss mitigation programmes has been discussed to an increasing extent in recent years (e.g. Kunreuther 2000). So far, however, implementation of this concept lags far behind its potential. The reasons are manifold. The public at large is often unaware of insurance mechanisms or has an idealistic perception of the function of insurance. In the insurance sector, competition and a short-term financial perspective do not create a favourable environment for actively promoting prevention and mitigation measures, as the time-scale for a possible positive outcome tends to be too long. A project aimed at loss prevention like the community classification scheme of the insurance-sponsored Institute of Business and Home Safety (IBHS) in the US, where communities are classified according to code compliance is so far unique.

The classic example of successful loss prevention in property insurance is the inspection of insured objects by fire engineers employed by insurance companies to make recommendations on enhanced fire protection. The level of fire protection is a well-established criterion for rating and PML assessment. As far as earthquake risk is concerned, similar initiatives were taken by private firms as a consequence of the shrinkage of insurance capacity after the Northridge earthquake in California. On the basis of risk management surveys, earthquake protection was improved and the insurance coverage bought was adjusted to the minimum demand or given up altogether in favour of direct investment in loss prevention.

Nevertheless, in natural hazards insurance, and especially in earthquake insurance, other features encourage loss reduction, namely risk-adjusted premiums and self-participation by the insured party.

Risk-adjusted premiums involve tariff schemes that reflect the actual risk level commensurate with the location and the constructional characteristics of the insured object. Such tariff schemes are increasingly being used on a global scale. But the correct application of such schemes presents a problem, and in actual practice, rates are mostly still dictated by pure competition. Sometimes, for instance, rebates are given for alleged compliance with anti-seismic building regulations. Often, however, code compliance has not been checked by insurance engineers or agents and, although stated, does not exist in reality. Therefore, awarding a rebate for code compliance can be counter-productive and even unjustified when it comes to older generation codes whose principal goal is avoiding loss of life rather than reducing monetary loss.

There are three types of self-participation. First, deductibles are expressed as a percentage of the sum insured or as a flat amount. Typical deductibles in earthquake-prone countries start at 2% and go up to 15% in highly exposed regions like California. But even in regions of moderate seismicity deductibles of 10% are used if insurance penetration and, consequently, potential catastrophe losses are high (e.g. in Israel). Insurance payments only commence in excess of the deductible. Second, (proportional) co-insurance is again expressed as a percentage of the sum insured. Under this arrangement the insured party carries a fixed proportion of each and every loss. Typical values range from 10 to 25% and reach a level of 70–85% in Tokyo Bay. Third, first loss co-insurance or liability limits can be expressed as a percentage or a flat amount. Here, the insurer pays either from the first penny, or after a deductible up to a certain limit. The loss amount that exceeds the limit is retained by the insured for its own account.

All of these elements can be combined and are accompanied by corresponding premium rebates. The greatest incentive to take loss prevention and reduction measures is given by proportional co-insurance of at least 10% or by deductibles of 5% or more, as the insured party has to carry a substantial portion of any loss on its own. The effectiveness of the above-mentioned elements depends to a critical degree on the actual spread of insurance. In this sense, a distinction can be made between 'free' insurance markets and countries where earthquake coverage is obligatory or semi-obligatory.

In an unregulated market that is completely exposed to competition, it is a delicate task to find the right balance between tariff elements geared to loss prevention and acceptability for the consumer, with the result that a sufficient spread of insurance is achieved or maintained. A common reaction in such cases is the 'zero option', i.e. no insurance and no loss reduction. This option is neither in the interest of the public, that at the very end has to pay the forthcoming losses without having set aside reserves beforehand, nor in the interest of the insurance industry, that wants to generate business. As a matter of fact, insurance conditions that are unattractive or in extreme cases completely unaffordable result in a situation where typically less than 10% of the people have any earthquake insurance at all. This applies, with few exceptions, to developed and less developed insurance markets as well. As a result of such a low market penetration, attempts to foster loss prevention by means of insurance become almost futile.

A much better environment for using insurance as a direct incentive or as an indirect contributor to loss reduction programmes is provided by insurance markets where the coverage has been made mandatory by government legislation, or is at least widespread. In these markets, attempts to educate and raise the awareness of the consumer by means of brochures and videos reach many more people and consequently have a greater chance of success than in free markets with low insurance penetration. Mortgage banks can play an efficient role in fostering high market penetration without the support of legal measures by requiring disaster insurance as a precondition for the loan, as practiced in Israel, Colombia and an increasing number of other countries. In addition, and even more important, all of the above cited direct measures like deductibles, can be brought to real fruition without leaving room for the 'zero option', if they are used, of course. If, instead of this, full coverage without substantial deductibles is granted under mandatory schemes, the goal of loss prevention is missed again. A portion of the premiums collected under such schemes can be invested in loss reduction programmes or in relevant research. The governmental Earthquake Commission (EQC) in New Zealand or the Swiss Earthquake Insurance Pool provide examples of such a policy.

(*f*) *Public private partnerships in natural disaster risk management*

The foregoing discussion has identified several mechanisms for mitigating losses from natural disasters. The challenge is to integrate these mechanisms into a secure and tight network of risk reduction measures.

(i) *Insurance pools*

Various solutions invoke the splitting of responsibilities between the parties. In New Zealand, for instance, the government owned EQC provides basic insurance coverage for every household up to an annually adjusted, actual building value. Additional coverage for the replacement cost can be obtained in the private market, as well as insurance for commercial and industrial risks and for business interruption. In Japan too, residential risks are covered to a large extent by the state-run Japan Reinsurance Company, whereas large businesses buy insurance in the private market, and the corresponding reinsurance is supplemented to a small extent by ART instruments like cat bonds. The concept of 'basic coverage' was also introduced by the California Earthquake Authority (CEA) in the aftermath of the Northridge earthquake in 1994 when earthquake insurance was difficult to obtain for homeowners.

The CEA is an example for an often-used concept in natural disaster insurance schemes: the insurance pool. An insurance pool involves every company participating in disaster losses in proportion to its market share in premiums. This concept ensures that companies avoid being too badly hit or even going bankrupt because of a disproportionately high loss burden from specific events. Recent examples of pool solutions are the Algerian Catastrophe Insurance Scheme, the Taiwan Residential Earthquake Insurance Pool (TREIP) and the Turkish Catastrophe Insurance Pool (TCIP), whereas schemes such as the US National Flood Insurance Programme, the Florida Hurricane Insurance Pool and pools in Switzerland, France and Spain have been in existence for a longer time. Pools can be supported either by private or by state reinsurance. They are also being considered now in several other countries in Europe, Latin America and Asia. Losses exceeding the capacity of the above-mentioned programmes usually fall under the responsibility of governments.

The Turkish scheme (TCIP) can be considered as a model case and is therefore introduced here in some more detail (Yunak 2004). It was designed with the aid of the Contractual Savings and Insurance Practice Operations Section of the World Bank. Essential elements of the TCIP are: mandatory scheme; no post-disaster loans to affected parties without insurance; 2% deductible +$ 55 000 limit; rating scheme graded according to hazard zone and risk type; and initially, complete risk transfer to global reinsurance. The scheme covers dwellings and small commercial risks, whereas larger commercial and industrial risks and high-value residential buildings are covered by the private market.

The involvement of capital markets in natural disaster coverage is still minor and limited to very few, well-developed markets. This may have to do with a very cautious attitude on the part of potential investors, the reasons for this being, on the one hand, a lack of confidence in risk-modelling tools for regions outside the US and Japan and, on the other, the general socio-economic situation of developing and emerging markets. On the buyer's (i.e. insurer's) side, the high price for such transactions as compared to conventional reinsurance must not be forgotten either. Nevertheless, the potential is there, and the successful placement of a catastrophe bond for the Taiwan scheme (TREIP) may herald future developments in this area.

What is almost completely missing so far are efficient incentives for code enforcement. The Turkish TCIP scheme started operations in late 2000 and has sold about 2 million policies to middle-class homeowners. The Turkish Catastrophe Insurance Pool represents an innovative concept for a less developed marketplace where code enforcement is meant to be linked to the availability of insurance protection and/or governmental disaster assistance. Establishing an efficient mechanism to guarantee code enforcement has failed so far, however

(Gülkan 2001). Also, with a 15% penetration rate achieved after 4 years of operation, the scheme cannot yet be considered a real success. The problem is that the scheme has not reached the status of a law and is only a decree in the legal sense. There are no sanctions against non-complying homeowners. As a consequence, current efforts by the pool authorities focus on turning the decree into a law.

Despite all the practical problems and limitations, the Turkish scheme illustrates the potentially helpful role of international organizations like the World Bank in designing and backing new, proactive strategies for risk prevention and reduction. Current projects sometimes extend beyond the classical domain of property insurance by also addressing low-cost housing, public infrastructure and crop insurance. Examples in this field are projects for natural disaster insurance schemes in Honduras and in India. Both projects have not yet materialized, however, and the feasibility of such schemes remains to be proven. A principal goal of such schemes is to achieve a wider spread of natural disaster insurance.

(ii) *Microinsurance: insurance for the poor*

A further development of making insurance accessible to more people is microinsurance. Poor people typically suffer most from natural disasters. They tend to live in the most vulnerable buildings. At the same time they usually do not have any basic understanding of what insurance means, and even if they had, they would lack access to insurance products. Microinsurance aims specifically at protecting the life and essential property of low-income people. In very general terms, microinsurance can be considered as a sort of co-operative or mutual insurance scheme on a small scale. The challenges of microinsurance are manifold. Addressing the local needs and conditions is indispensable. Therefore, microinsurance schemes usually take the form of a partnership of an internationally operating insurer who contributes the insurance know-how and a local institution that cares about the local clients' demands. Often the clients are illiterate and make their living in the informal economy, which requires innovative distribution channels and payment modes. A good summary can be found in Churchill *et al.* (2006).

3. Extreme natural events

What are 'extreme natural events'? A strict definition is difficult as there is a smooth transition from 'normal' and 'big' events to exceptional ones. There are two criteria for an extreme event: the occurrence probability and the area affected. Regarding the probability it is common practice in natural disaster insurance to steer the business on the basis of loss scenarios whose regional frequency is once in 250–1000 years, at maximum. Examples include an earthquake in Tokyo, a double-landfall hurricane affecting Florida and the US Gulf Coast, or a great winterstorm affecting NW and Central Europe. As to the area affected one may consider as an extreme such events that have serious regional or even global consequences. A good example would be a great volcanic eruption with an impact on the global climate. Finally, to turn an extreme event into a disaster it must affect a populated area. It does not make sense from a risk perspective to consider the regional frequency for events with a global impact. Both their global impact and their global probability have to be taken into account. In conclusion, and in an insurance context, we classify as extreme events those whose occurrence probability is beyond the common planning horizon, i.e. below once in 1000 years, be it in a global or a regional reference frame.

(*a*) *The South Asian tsunami of 26 December 2004: a wake-up call*

In terms of human losses, the South Asian earthquake and tsunami disaster, with about 230 000 victims, was the biggest natural disaster since the Tangshan earthquake in China in 1976. Total material losses amounted to approximately US$ 10 bn, while insured losses were below US$ 1 bn. The national economies of the various countries were affected in different degrees. The Maldives, that depend almost entirely on the tourism industry, and Sri Lanka, again largely dependent on tourism and fishing, were the most severely hit. But in spite of the staggering death toll, the impact on Indonesia's gross domestic product was only nominal, and in Thailand too, the economy was not affected to a really significant extent. In summary, there was an enormous death toll, but the financial impact of this gigantic human disaster was insignificant on a global and partially even on a national scale.

Notwithstanding the small volume of insured losses and the fact that the South Asian tsunami was not a truly rare event in a worldwide context, it increased the sensitivity for extreme natural disasters. First and foremost, the question was raised as to what the loss potential of similar events in other ocean basins might be. The sheer extent of the affected region of the South Asian tsunami was unprecedented as far as the insurance industry was concerned. Past ocean-wide tsunamis, such as the 1964 and 1960 events in the Pacific basin, occurred too early to be of real concern to insurance. Losses were incurred not only in the countries directly affected but also in countries located far away, where the event brought suffering and death to several thousand tourists. In consequence several lines of insurance were affected: beyond property insurance, i.e. the insurance of buildings and their contents, machinery and installations, above all personal lines: life, health, workers compensation, personal accident and travel insurance. The complexity of the loss had much in common with the hitherto greatest insurance event, the terrorist attack to the World Trade Center on 11 September 2001. In consequence, extreme events in general received renewed attention within the financial sector. A prominent example is the possible flank collapse at the Cumbre Vieja volcano on La Palma, and the ensuing large tsunami postulated by Ward & Day (2001).

(*b*) *The challenge of extreme natural events*

Regarding the risk management of extreme disasters, the same principles and procedures can be applied as those specified already in the context of classical natural hazards. This means that the hazards have to be identified and the related risks evaluated. Then, the potential losses have to be controlled, and prevented and mitigated as far as possible. The particular challenge of very rare, extreme events lies in the fact that such disasters have not yet been experienced in documented human history. But their impact could be huge, if they happened in our modern world. Therefore, their effects must be reconstructed on the basis of geological and geomorphological investigations and theoretical modelling of the physical processes involved. Both these undertakings are fraught with considerable uncertainties.

It is only partially possible to draw analogies from known events in the recent past. For instance, the South Asian tsunami of 26 December 2004 may well serve as a blueprint for damage patterns of similar future events in other regions. Another example is Hurricane Katrina of August 2005: the degree of destruction it inflicted on the US Gulf Coast would probably not be exceeded even by a strong tsunami. But, as the Boxing Day 2004 tsunami in South Asia demonstrated, the length of coastline affected could be greater.

There now follows a brief summary of knowns and unknowns and the description of a rational approach to treating extreme events in accordance with the risk management principles.

(i) *Hazard identification*

A wide range of extreme natural events are a threat to the insurance industry. Such events are now identified:

Great volcanic eruptions are called 'super-eruptions': some recent examples are the Toba eruption on Sumatra 74 000 years ago, with an eruption volume of about 3000 km^3 (as compared to 18 km^3 in the famous Krakatoa eruption of 1883) and the Oruanui eruption in New Zealand 26 500 years ago with 500 km^3 eruption volume (e.g. Mason *et al.* 2004; Self 2006).

Giant submarine landslides occur on continental slopes (Masson *et al.* 2006). The best-documented cases are the Storegga slides of west of Norway, the last of which occurred 7000 years ago. Its volume was about 2500 km^3 (e.g. Harbitz 1992).

Giant landslides also result from flank collapses of volcanic islands in the ocean or on coasts. In principle, every volcano in the ocean is an unstable edifice whose over-steepened slopes collapse from time to time in catastrophic slides or slide series. About 20 such catastrophic episodes have been documented for the Canary Islands within the last two million years (e.g. Masson *et al.* 2006), and several have been documented from the Cape Verdes, the volcanic islands of the Caribbean (Le Friant 2001), the Hawaiian Islands and Reunion.

For meteorite impact, objects with a diameter of 100 m, which is the smallest size necessary to reach the earth's surface, hit the earth on average once in several thousand years. Ten kilometre objects like the one which is blamed for the mass extinction marking the boundary between the Cretaceous and the Tertiary epochs 65 Myr ago happen once in about 100 000 000 years. In the only documented meteorite fall, the Tunguska event of 1908, the object was too small to reach the earth's surface and exploded in the atmosphere. The shock wave nevertheless flattened about 2000 km^2 of forest (e.g. Morrison 2006).

A consequential effect common to all these hazards when they happen in oceans is tsunami generation. Other events, which are only briefly mentioned here, are the sudden release of methane hydrates buried under the ocean bottom (such an event may have caused the Storegga slide mentioned above), abrupt climate change, cosmic storms, i.e. episodes of exceptionally high magnetic particle flux from the sun, and reversals of the earth's magnetic poles. Understanding atmospheric and hydrospheric hazards emanating from climate change, e.g. perturbations in ocean currents like the Gulf Stream (e.g. Bryden *et al.* 2005) is important and even directly relevant to modelling the global climate effects of great eruptions and impacts. Events like cosmic storms have not been within the focus of research so far, but they may be highly threatening to a civilization that relies so heavily on electronic devices as is the case nowadays.

(ii) *Risk assessment*

Risk assessment involves a (probabilistic) assessment of the hazard and combining the hazard with data on the vulnerability of objects and communities. A quantitative, probabilistic assessment of the hazard suffers from the lack of reliable and cross-checked event catalogues. The situation is best for earthquake-induced tsunamis (National Geophysical Data Center NGDC: tsunami database, online), but there is room for improvement even here. This applies to an increasing degree to other events like volcanic flank collapses in ocean islands and submarine slides. Also, the inventory of great volcanic eruptions has grown (Mason *et al.* 2004), but it can hardly be considered complete. Much more geological and geophysical fieldwork is needed in order to improve the existing inventories of events. The new technique of side-scan SONAR for mapping oceanic topography has great potential for enhancing inventories of past submarine slides. Regarding meteorite impact, the Spaceguard survey has improved the data inventory for so-called NEAs (near-earth asteroids) substantially. By the end of this decade, it should have identified 90% of all asteroids, but bringing down the threshold size to smaller and more frequent earth-encountering objects would require a substantial additional effort (Morrison 2006).

The challenges of hazard assessment are discussed in more detail below taking the example of tsunamis. Empirical evidence for vulnerability is usually lacking due to the rare occurrence of extreme events. But it is often possible to draw analogies from smaller-sized or similar events such as 'normal' volcanic eruptions, explosions or firestorms. Disasters like the South Asian tsunami in 2004 offer a unique chance to collect empirical loss data. There is, however, a further complicating effect over and beyond the lack or scarcity of empirical loss data: losses from extreme natural events are often the end result of a combination of primary and secondary hazards in event chains. Furthermore, losses can accumulate from many countries and from different lines of business. To some extent, this was demonstrated by the Sumatra earthquake and the ensuing tsunami where losses occurred in all sorts of insurance classes. Identification of all possible loss agents is of prime importance in order to avoid hidden loss accumulations. For example, the final loss from a meteorite impact on land stems from various components. It starts with the shock wave and then moves on to falling objects and wildfires, and finally extends to all the consequences of the ensuing climatic perturbations and their effects on the built environment as well as on food production. Estimating the vulnerability of the built environment to these various hazards and assessing consequential losses under non-property-related insurance lines represents a particular and formidable challenge, for the lack of actual loss experience.

(iii) *Risk control*

There is a common misconception about extreme natural disasters that control and prevention measures would be useless because of the sheer size of such events. Such an attitude denies the fact that there is a smooth transition from more common to extreme hazards. Furthermore, it has been demonstrated by Ward & Asphaug (2000) that the total risk of meteorite impact is dominated by objects with a diameter of some 200–300 m, i.e. just big enough to survive the plunge into the upper atmosphere. The frequency of such an impact is about once in 10 000 years. This principle can also claim validity in respect of other hazards such as large volcanic eruptions and is dictated by the exponential decrease in frequency with increasing event size. The decrease is even more pronounced in the extreme tail of the frequency distribution.

The list of measures for risk control presented in §2 is also suited to handling extreme events, but with somewhat differing weights regarding the various possible choices. As to calculating technical rates, extreme events are so rare that calculating an insurance rate ends up in values close to zero. They are, however, the ultimate expression of low-probability/high-consequence events, and it is therefore absolutely imperative to limit the liability arising from them. This implies the need for exact knowledge of what is covered under existing insurance contracts. However trivial this may sound, it is very important because unclear and misleading terms are not unusual in insurance policy wordings. In addition, the impact of extreme disasters on the capital markets has to be considered and planned for, because it reduces the value of the assets and the capital strength of insurance companies. The combined effect of high material losses and reduced asset values was seen after the terrorist attack of 11 September 2001, although there was no causal connection between the two phenomena in this case.

Arguably, such considerations are philosophical in view of the extremely low likelihood of a meteorite impact in a densely populated and well-developed region. As risk assessment is also fraught with large uncertainties, as demonstrated above, a general exclusion from coverage may turn out to be the *ultima ratio* for most of these events, at least given the present state of knowledge. But drawing a line between what at first sight appears to be an insurable peril, e.g. a volcanic eruption, and what becomes an uninsurable one once the event exceeds a certain threshold is a problem that has not yet been considered systematically, let alone solved, by the insurance industry.

And what about prevention, which plays such an important role in connection with ‘classical’ natural perils? Indeed, many prevention measures, which work in the case of earthquakes, e.g. will also have a positive effect on other perils, at least to some extent. Chapman (2003) provides an excellent discussion of options for handling meteorite impact scenarios. He makes the interesting argument that this most threatening natural peril seems to be the only one where prevention of the event itself, not only of the ensuing losses, seems feasible, by diverting the celestial body away from its dangerous track through human intervention. But what appears technically feasible can have serious political and human implications, ranging from intentional misuse of the technology to unintentional failure of the mission (Morrison 2006).

Whereas the theoretical possibility of completely preventing an extreme event is unique to the impact hazard, all the aforementioned extreme disasters have one thing in common: the, usually ample, warning time. These times range from a few minutes for coastal sites close to tsunami sources to several years for impacts. Great volcanic crises are somewhere in between with warning times of weeks to months. A practical problem is, however, that there are no criteria to assess the magnitude of a pending eruption from the precursory activity. And surprise eruptions are still possible due to gaps in the observational network. In an insurance context, the possibility of early warning is of limited value as regards reducing the risk of material losses. People can be evacuated—although the complexity of such an operation is unimaginable in the case of a truly large event that may affect an area the size of a country or continent. But moving buildings and infrastructure is impossible.

(*c*) *The case of tsunami*

Of all extreme events, tsunami is the peril that deserves most urgent attention. This derives from the fairly high frequencies due to the variety of causative phenomena. In decreasing order of frequency, tsunamis are caused by: earthquakes, often in combination with concurrent submarine slides; by submarine slides on their own; by volcanic eruptions and by meteorite impact. Geomorphological field work on several coasts has documented prehistoric and even historic tsunamis of unknown origin within the last 10 000 years whose force must have been stronger than that observed in the South Asian tsunami of 2004. This can be deduced from the huge boulders displaced on higher ground and inland by the tsunami. Interestingly, some observations relate to regions that are commonly not considered as exposed to earthquake tsunami, e.g. the Bahamas and the ABC (Aruba, Bonaire, Curaçao) islands in the South Caribbean and Majorca (Scheffers & Kelletat 2003). Of course, numerous earthquake sources are known in the Caribbean region, and there is a voluminous catalogue of tsunami events. But the orientation and earthquake potential of the known faults cannot explain the field observations. Majorca is a different case that may even serve as an explanation: the coastal region of North Algeria provides an earthquake source as demonstrated in the Boumerdes earthquake of 2003. But prehistoric tsunamis at about 500 BP and earlier must have been much bigger than would be expected from the typical size of earthquakes offshore Algeria. A possible explanation is huge submarine slides released by such earthquakes, but more work is needed to prove such a hypothesis. Eventually, also the Thai coast had been considered as tsunami-free before the 2004 tsunami, due to simple lack of knowledge.

In principle, constructing a global probabilistic tsunami hazard map for earthquake tsunamis appears feasible. But converting the available data into a probabilistic hazard assessment requires a great deal of additional effort. A straightforward and logical approach is presented by Ward & Asphaug (2000) for meteorite tsunamis, irrespective of the fact that the base assumptions on the underlying physical processes they use in their modelling are contentious. The procedure is derived from the well-established probabilistic seismic hazard assessment method and can safely be transferred to earthquake tsunami modelling. The origin and propagation of earthquake tsunamis is fairly well understood. For local applications, the main problem lies in modelling the run-up heights. The physical process controlling run-up is well-known, but the crucial data on offshore coastal topography only exist for a small section of coastal regions globally. This is the critical part as local effects are the main control on run-up and inundation, and therefore on loss of life and damage to property. It would be an enormous undertaking for all parts of the world that are threatened by tsunamis, but surely worthwhile for the most exposed places. A further problem in global earthquake tsunami modelling is the fact that it is sometimes difficult to distinguish between earthquake-generated and slide-generated tsunamis, which often occur concurrently with true earthquake tsunamis. Prominent examples are the Aleutian earthquake of 1946 and the Alaska earthquake of 1964, both of which produced earthquake-induced, ocean-wide tsunamis and consequential slide-induced, local tsunamis as well. A further complication is that some tsunamis—including the 2004 event—do not leave long-lasting traces that would be amenable to later geological research.

Earthquake tsunamis have extended sources. Other tsunami causes such as slides and meteorites can be considered point sources. This constitutes an important difference regarding wave propagation, as point sources tend to produce comparatively shorter wavelengths which are dispersed more quickly with increasing distance than the longer waves generated by extended sources. The earlier model of the La Palma slide by Ward & Day (2001) uses several unsatisfactory approximations. It treats tsunamis as shallow water waves and thus neglects nonlinearities in the tsunami generation process. As to wave propagation, it considers only geometrical spreading and fails to address frequency-dependent wave dispersion. In the meanwhile more sophisticated codes, such as the SAGE code developed at the Los Alamos National Laboratory (Gisler *et al.* 2005) have become available. The SAGE code models slide tsunamis in a more realistic manner as intermediate waves of short period and wavelength. Nonlinearity in the generation process is handled by Navier Stokes modelling. The decay rates that include wave dispersion produce much less pronounced far-field effects. The modelling uncertainty already starts, however, with the assumptions on the slide mechanism, a single block slide as opposed to slide series, and on slide velocity, and it continues with the way in which the slide energy is transformed into tsunami waves. This is not to rule out the possibility of landslides being emplaced in one more or less coherent piece, as argued for the Hawaiian Alika slide by McMurtry *et al.* (2004). But the question is, if this is the exception rather than the rule. Even if it were true for the Hawaii region, it is not necessarily transferable to the Canary Islands. Indeed, the work of Masson *et al.* (2006) and co-workers suggests emplacement in event series as being the common mechanism there. More observational data on slide mechanisms and velocities and their coupling to wave generation are urgently needed in order to constrain the assumptions which go into the modelling process. A situation as now where estimates of tsunami height on the east coast of the US for the La Palma scenario vary from a few centimetres to 25 m is intolerable for any decision-maker.

To assess the risk in terms of expected losses, hazard assessment has to be supplemented by vulnerability data, which are scarce. For example, along the affected Thai coast, the Boxing Day 2004 tsunami produced an average loss of about 4% of the total exposed values in the stricken municipalities. Whereas this may seem surprisingly low, the fact must be taken into account that the damage was heavily concentrated in the first row of buildings and that the average figure includes a large number of unaffected structures farther inland. Using the 4% figure and assuming a recurrence period of 1000 years, not unreasonable for the Thai coast, this translates into an annualized loss of 0.004%. This gives a very rough idea on the required average insurance rate for this most frequent type of extreme event. Clearly, this average figure would be higher along the northwest coast of Sumatra and probably also the east coast of Sri Lanka, and should be differentiated according to location, distance from the coast and construction type.

Earthquake tsunamis cannot be considered uninsurable, with the usual policy or treaty limits in force, even for the most serious scenarios. Such scenarios could be, e.g. a repetition of the earthquake offshore Portugal in 1755, when the ensuing tsunami not only destroyed nearby coasts but even affected the Lesser Antilles with waves up to 7 m. Another example would be a tsunami triggered by a magnitude 8 earthquake on the Aegean subduction zone, that could affect a large portion of the coasts in the eastern Mediterranean, or a more local tsunami caused by an earthquake on the Nankai trough south of central Honshu. In respect of earthquake tsunamis, assessing the hazard and loss potential is possible. This also applies to volcanic eruptions as a causative mechanism, but with a higher uncertainty regarding event frequencies and propagation of the tsunami waves. Tsunamis due to submarine slides and meteorite impacts are a different matter. As long as such enormous disparities in hazard assessment exist as discussed above, the insurability of non-earthquake-generated tsunamis is an open issue.

4. Conclusions

In conclusion, the challenge of extreme natural disasters faced by the insurance industry is in principle no different from the challenge posed by more common natural disasters like earthquakes, windstorms and floods. Complete exclusions from the coverage have probably to play a greater role in the case of extreme hazards. An important first step is to identify and eliminate ambiguous policy wordings. They can produce unexpected losses, for which the corresponding premium may not have been charged. An example is the term ‘tidal wave’, that could lead to unintentional tsunami coverage under flood policies. As regards proactive risk prevention, nothing specific can be achieved over and beyond the measures used for the more common risks. The unique feature that some or even ample warning time will usually be available does not mean much in terms of reducing and preventing material losses. A systematic discussion on how the insurance sector should handle the risk of extreme disasters has not yet taken place, and is indeed overdue.

Beyond the field of insurance, an all-encompassing policy for extreme events would have to take into account the fact that mankind (and the financial sector) has also other urgent issues, and more frequent disasters, to deal with. Consequently, a policy for handling extreme disasters must be weighed against the need to deal with more urgent phenomena like hurricanes on the scale of Katrina, which affected not only the coast of Mississippi and New Orleans but also the global oil market, or risks inherent in the capital markets, or political and socio-economic crises like the civil wars, droughts and famines in Africa.

The author would like to thank the Royal Society of London for the invitation to the stimulating Workshop on Extreme Natural Hazards. Special thanks are owed to Steve Sparks, Bill McGuire, Galen Gisler and an anonymous reviewer for valuable discussions and suggestions that much improved the quality of the paper.

References

Bryden, H. L., Longworth, H. R. & Cunningham, S. A. 2005 Slowing of the Atlantic meridional overturning circulation at 25° N. *Nature* **438**, 655–657. (doi:10.1038/nature04385)

Chapman, C. R. 2003 How a near-earth object impact might affect society. In *Proc. OECD Workshop on Near-Earth Objects: risks, policies and actions, Frascati, Italy.*

Churchill, C., Reinhard, D. & Qureshi, Z. 2006 Microinsurance—making insurance work for the poor. *Report Summary Microinsurance Conference, Schloss Hohenkammer, Munich*, 6 pp.

Gisler, G., Weaver, B. & Gittings, M. 2005 SAGE calculations of the tsunami threat from La Palma. In *Proc. 2nd Int. Tsunami Symp., Chania*, pp. 65–71.

Gülkan, P. 2001 Rebuilding the Sea of Marmara region: recent structural revisions in Turkey to mitigate disasters. In *Proc. Wharton-World Bank Conference on Challenges in Managing Catastrophic Risks: lessons for the US and emerging economies, Washington, DC.*

Harbitz, C. B. 1992 Model simulations of tsunamis generated by the Storegga slides. *Mar. Geol.* **105**, 1–21. (doi:10.1016/0025-3227(92)90178-K)

Kunreuther, H. 2000 Mitigation and financial risk management for natural hazards. In *Proc. 6th Int. Conf. Seismic Zonation, Palm Springs (CD-ROM).*

Le Friant, A. 2001 Les destabilisations de flanc des volcans actifs de l'arc des Petits Antilles: origins et consequences, These de Doctorat, Université de Paris VII, 377 pp.

Mason, B. G., Pyle, D. M. & Oppenheimer, C. 2004 The size and frequency of the largest explosive eruptions on Earth. *Bull. Volcanol.* **66**, 735–748. (doi:10.1007/s00445-004-0355-9)

Masson, D. G., Harbitz, C. B., Wynn, R. B., Pedersen, G. & Løvholt, F. 2006 Submarine landslides: processes, triggers and hazard prediction. *Phil. Trans. R. Soc. A* **364**, 2009–2039. (doi:10.1098/rsta.2006.1810)

McMurtry, G. M., Fryer, G. J., Tappin, D. R., Wilkinson, I. P., Williams, M., Fietzke, J., Garbe-Scoenberg, D. & Watts, P. 2004 Megatsunami deposits on Kohala volcano, Hawaii, from flank collapse of Mauna Loa. *Geology* **32**, 741–744. (doi:10.1130/G20642.1)

Morrison, David 2006 Asteroid and comet impacts: the ultimate environmental catastrophe. *Phil. Trans. R. Soc. A* **364**. (doi:10.1098/rsta.2006.1812)

Munich Reinsurance Company 1998 World map of natural hazards, 55 pp.

Munich Reinsurance Company 2003 NatCatService—a guide to the MR database for Natural Catastrophes, 20 pp.

Munich Reinsurance Company 2005 TopicsGeo—annual disaster review 2004, 56 pp.

National Geophysical Data Centre NGDC: tsunami database. http://www.ngdc.noaa.gov/seg/hazard/tsu_db.shtml.

Scheffers, A. & Kelletat, D. 2003 Sedimentologic and geomorphologic tsunami imprints worldwide—a review. *Earth Sci. Rev.* **63**, 83–92. (doi:10.1016/S0012-8252(03)00018-7)

Self, S. 2006 The effects and consequences of very large explosive volcanic eruptions. *Phil. Trans. R. Soc. A* **364**. (doi:10.1098/rsta.2006.1814)

Ward, S. N. & Asphaug, E. 2000 Asteroid impact tsunami: a probabilistic hazard assessment. *Icarus* **145**, 64–78. (doi:10.1006/icar.1999.6336)

Ward, S. N. & Day, S. 2001 Cumbre Vieja Volcano—potential collapse and tsunami at La Palma, Canary Islands. *Geophys. Res. Lett.* **28**, 397–400. (doi:10.1029/2001GL013110)

Yunak, H. 2004 Turkish Catastrophe Insurance Pool. In *Proc. AIO/UNCTAD Conference on Insurance and Reinsurance of Catastrophic Risks for Long-Term Development in Africa, Casablanca. Morocco* (CD-ROM).