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Extreme natural hazards: population growth, globalization and environmental change

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Mankind is becoming ever more susceptible to natural disasters, largely as a consequence of population growth and globalization. It is likely that in the future, we will experience several disasters per year that kill more than 10 000 people. A calamity with a million casualties is just a matter of time. This situation is mainly a consequence of increased vulnerability. Climate change may also be affecting the frequency of extreme weather events as well as the vulnerability of coastal areas due to sea-level rise. Disastrous outcomes can only increase unless better ways are found to mitigate the effects through improved forecasting and warning, together with more community preparedness and resilience. There are particular difficulties with extreme events, which can affect several countries, while the largest events can have global consequences. The hazards of supervolcanic eruptions and asteroid impacts could cause global disaster with threats to civilization and deaths of billions of people. Although these are very rare events, they will happen and require consideration. More frequent and smaller events in the wrong place at the wrong time could have very large human, environmental and economic effects. A sustained effort is needed to identify places at risk and take steps to apply science before the events occur.

Keywords: disasters; extreme events; geophysics; globalization; natural hazards; risks

1. Introduction

The natural world can be a dramatic, dynamic and dangerous place. Life ultimately thrives on Earth because it is a dynamic planet, but the extremes of nature can threaten the survival of individuals, communities and even species. Every year television pictures and newspapers report scenes of devastation, despair and death caused by huge earthquakes, floods, droughts, cyclones, landslides and volcanic eruptions. The Asian tsunami, with around 250 000 deaths, huge economic losses and long-term damage to development programmes in the affected countries, brought home to the world the realities of the danger. We live in times of increasing vulnerability to extreme natural hazards. The

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

Asian tsunami was a truly global disaster which affected not only many countries in the region, but also tourists from the developed world on holiday in southeast Asia. For example, the incident represented the greatest loss of life of Swedish citizens from a natural event. Again, Hurricane Katrina, which devastated New Orleans in September 2005, had global effects on oil prices and showed that even the world's most powerful and wealthy country experiences difficulties with the extremes of nature.

Science plays a critical role in understanding and mitigating the effects of extreme events. Like many individuals and organizations, the scientific community experienced a mixture of profound sympathy for the victims of the Asian tsunami and introspection on how such events could be better prepared for and faced. As a consequence, the Royal Society of London decided to hold a fast-track discussion meeting to examine the role of science and technology in ameliorating the effects of extreme natural hazards. Problems related to natural catastrophes go well beyond scientific and technological approaches. Economic, political, cultural, sociological and psychological factors are of huge importance, as is the role of governments, international agencies and NGOs in responding to crises. In recognition of the importance of non-scientific issues and perspectives, the meeting also involved representatives from a broad base of disciplines and organizations, and included policy-makers and decision-takers. The concept behind the meeting was not only to review the frontiers and challenges of the relevant science, but also to develop dialogue with other disciplines about how to communicate and apply science effectively.

This contribution provides a synopsis of some of the key issues that emerged from the meeting. The major natural hazards in question are reviewed by McGuire (2006) and more specifically by the following specialist contributions on particular hazards. We thus do not here review the hazards themselves, but focus on generic issues, many of which are common across hazards. The objective of the meeting and this publication is to address how science can be developed and employed to do better.

2. Natural catastrophes are increasing

A disturbing message from the meeting is that the frequency of major natural catastrophes is increasing (Smolka 2006). These statistics were brought alive by the Asian tsunami, Hurricane Katrina and the Kashmir earthquake in the year prior to the meeting. Although droughts were not discussed specifically, the famines in Niger, Mali and Mozambique could be added to the list of natural catastrophes for 2005. The southeast Asia tsunami and Kashmir earthquake illustrated the vulnerability of developing countries, resulting in terrible death tolls, great suffering and whole communities being destroyed. Hurricane Katrina showed that extreme events can have global economic effects as well as causing severe destruction and torment, particularly for the poor. For the foreseeable future, the world can expect several natural events per year that can kill tens of thousands of people, adversely affect millions of people and cause severe economic and social disruption. A disturbing photograph demonstrating human tragedy caused by natural disaster is shown in figure 1. For further images

Figure 1. Human misery caused by natural disasters. Image reproduced courtesy of Morteza Talebian (Geological Survey of Iran).

see electronic supplementary material. Several speakers forecast, reluctantly, that an event that would kill more than a million people in the next few decades was likely to occur.

One possible explanation for the increasing devastation brought by natural catastrophes is that the frequency of natural events is increasing. A different and more likely explanation, however, is that there is increased influence of events due to ever increasing vulnerability arising from larger populations in high risk locations. Human activities are also a critical issue in exacerbating vulnerability to natural hazards, ranging from anthropogenic climate change at one extreme (Mitchell *et al.* 2006) to local deforestation and changes in land use at the other (Wheater 2006). Nevertheless, real increases in the rates of large magnitude events are worth brief consideration. The major tectonic hazards of earthquakes and volcanic eruptions are governed by plate tectonics and typically involve stochastic processes. Adjustments and changes in plate motions and arrangements are exceedingly slow, operating on time-scales of millions of years. On time-scales of decades and even the millennia relevant to human affairs, the rates of these events are relatively steady and unchanging on a global scale. Earthquakes and volcanic eruptions taken globally approximately follow a Poisson (random) distribution in time (Woo 2000). However, there can be spatial and temporal variations in rates of events with distributions that may be clustered or more regular in time at an individual volcano or along a particular fault system, where the occurrence of events is controlled by smaller-scale, local processes and effects (Kanamori 2006). There can also be issues related to rare and extreme events that are not well represented in the very short period of recorded history (*ca* 2000 years).

Notwithstanding these possible variations, there is no evidence that the increase in devastating earthquakes, for example, represents some unexplained and indeed very unlikely increase in plate activity.

The case for increasing natural events due to environmental change, in particular of global climate, is different. Since 1960, the number of tropical cyclones that have been classified as categories 4 and 5 has doubled. This change could be due to natural variability; though a systematically warmer atmosphere and ocean could also explain the change. A warmer Earth has more energy and models of the atmosphere suggest more variability and more extreme events. For tropical cyclones, for example, warmer sea surface temperatures in sub-tropical latitudes could be a factor in increasing the rates of extreme events. The question of whether global warming can cause increases in extreme weather events is still unresolved, but is being taken very seriously by atmospheric scientists (e.g. Karl *et al.* 1997; Mitchell *et al.* 2006). The other less contentious effect of global warming is sea-level rise, which increases the vulnerability of coastal communities to natural hazards, including floods, storm surges and tsunamis. Wheater (2006) estimated that storm surges with a current recurrence rate of 1 in 60 years may change to 1 in 2 years by the end of the century, based on a 0.5 m rise in sea level. While quantitatively such estimates have large uncertainties, qualitatively the trend must be correct.

Consensus is definitely emerging that the major causes of increasing natural catastrophes are directly related to human activity. Obvious effects include population growth and urbanization, with spectacular growth of megacities over the last few decades, and environmental degradation and change caused by human activities. The world's population is becoming more concentrated in urban areas rather than in the less densely populated rural areas. In 2007, for the first time in human history, more people will live in urban centres than in the countryside. Taken together, these changes make communities much more vulnerable to natural hazards. Jackson (2006) gives the striking example of Iran, where villages have grown into large towns and in the case of Tehran into a megacity with 12 million inhabitants. Tehran is built on an active fault system with associated water springs, which allowed the initial habitation to develop. Tehran has been destroyed by earthquakes on four occasions over the centuries, when it was a small provincial town of no political importance. The buildings in Tehran are similar to those of other Iranian cities, which have been devastated by earthquakes with very high mortality rates (60 to 80% of the resident population being killed). Several thousand deaths 100 years ago from a population of 10 000 was a tragedy; up to a million deaths in a city of 10 million would be a momentous calamity. Many megacities around the world have developed in the last few decades in highly vulnerable sites; thus an event that dwarves the Asian tsunami seems inevitable.

Environmental degradation and change also affect vulnerability, usually in adverse ways. For example, urban development and some agricultural practices reduce infiltration so that floods become worse even if the meteorological processes remain the same (Wheater 2006). Destruction of mangrove swamps in Sri Lanka increased the vulnerability of coastal communities to the tsunami (Kesavan & Swaminathan 2006). Deforestation can cause changes in rainfall patterns and infiltration, resulting in more devastating floods. There is, for example, evidence that environmental changes in the mountain catchment areas in the Himalayas have increased run-off and major floods, adversely affecting Bangladesh. In the

SW Province of Cameroon, shanty towns have built up at the base of steep slopes, which have become unstable due to undercutting; the result has been landslides almost every rainy season with many deaths. In December 1999, flash floods in Venezuela killed more than 30 000 people, many in modern high-rise buildings, under similar circumstances of environmental degradation related to unplanned development.

3. The influence of extreme events

The Asian tsunami has been described as a wake-up call for the world. This event affected 11 countries directly and there was loss of life from over 50 countries, including tourists from the affluent north. Hurricane Katrina affected oil prices for a few months, but financially the effects may not be long-lasting on a global scale. However, scientists are well aware that there are extreme natural events that can have much greater effects and consequences. Extreme events are rare, but can have an impact on humanity on a global scale. The possible consequences of extreme events include: global economic crises; many millions to tens of millions of deaths; catastrophic and irrecoverable destruction of megacities and possibly whole countries; global disruption of food supplies, transport and communications; severe climate states; and environmental pollution on a global scale. These effects may in turn lead to famine, disease, political strife, collapse of social order, failure of international and national organizations in the face of overwhelming effects and even possibly the outbreak of wars and collapse of civilization. The most extreme and rarest events (asteroid impacts and possibly the largest super-eruptions) may threaten species survival. Unfortunately, such apocalyptic visions are not science fiction and are not scare mongering. The evidence for natural events on the scale necessary for global catastrophe is robust; humanity will eventually have to face and attempt to survive them.

It is only very recently that the threat from extreme events has been recognized beyond specialist scientific circles. This recognition comes at a critical stage in human development as the world becomes increasingly interdependent and increasingly vulnerable. Globalization seems irreversible and concepts of cooperation, international agreements and global community have emerged. Many complex factors have led nations to cooperate and take collective actions in the last few decades. Response to environmental change has been one of them. The ozone problem due to chlorofluorocarbon pollution of the upper atmosphere is a strikingly successful example, with the Montreal Protocol resulting in international action to prevent a very serious threat. Global warming is an even more profound threat, where international action and agreement to reduce carbon emissions is at least recognized as high on the agenda, even if the mitigation steps are proving so difficult to implement. Following the Asian earthquake, the Hyogo agreement represents the first time that the international community has recognized the need for collective and coordinated action to mitigate the effects of natural hazards. Such developments are grounds for cautious optimism that humanity can unite to reduce the effects of environmental change and natural hazards. Only international efforts can address extreme hazards; even the most powerful country on Earth has difficulties when the magnitude of the events is sufficiently large.

The first recognition that there can be global catastrophes came from the serious consideration given to asteroid impacts. This interest emerged from advances in astronomy, from observations of numerous impact craters on other planets and from research concerned with the consequences of nuclear war. In the 1970s, scientists alerted the world to the severe and catastrophic effects of nuclear war. Apart from the direct destruction and radiation, atmospheric models indicated that the Earth could be plunged into a nuclear winter with severe conditions lasting for many years and threatening human survival. These warnings from sections of the science community arguably had a major role in persuading politicians from rival power blocks, ideologies and political systems that there was an urgent need to control the proliferation of nuclear arms and reduce tensions that might lead to nuclear war. Several scientific advances coincided with the nuclear war issue to show that global disaster with similar effects could also happen by asteroid impact. The exploration of the solar system and discovery of geologically recent giant impacts on Earth made it clear that asteroid impact is a ubiquitous feature of the solar system and part of the Earth's natural environment. Sufficiently large impacts can cause mass extinctions. The US and UK Governments commissioned panels of eminent scientists to report on the threat to Earth from Near Earth objects (NEOs) and this in turn led to a programme of systematic tracking of all space objects that might collide with the Earth, as described in much more detail by Morrison (2006). Asteroid impacts happen all the time; a little known but dramatic fact is that an explosion with energy equivalent to a Hiroshima-sized nuclear explosion occurs on average every year in the upper atmosphere. Fortunately, the atmosphere offers great protection to the Earth and only the largest, but also very rare, objects can get through to the Earth's surface. NEO studies, stimulated by governmental concern, have been a success. By 2008, 90% of NEOs greater than 1 km diameter in the solar system will have been identified. Their orbits can be predicated with great accuracy. It seems likely that any object that has a chance of colliding with the Earth should be identified many years before a potential impact. It also appears that the technology may exist, at least in principle, to attempt to divert such objects from collision.

Following on from the raised awareness of NEOs and persuading governments to take the issue seriously, parallel activity is now developing for very large magnitude volcanic eruptions. As with asteroids, the effect of large eruptions has been popularized by the media in TV dramas, documentaries, movies and popular books. The dramatic, albeit scientifically poorly defined, supervolcano and super-eruption are new terms that have raised public awareness. An explosive eruption on the scale of the eruption of Toba 74 000 years ago is perhaps the only other kind of natural hazard apart from NEOs that might cause global catastrophe (McGuire 2006). However, volcanic events that could devastate large regions need not be so extreme. The Campanian eruption, which originated from the Bay of Naples *ca* 38 000 years ago, would be a catastrophe of apocalyptic proportions for countries in the central and eastern Mediterranean, as well as disrupting life internationally on an enormous scale and plunging the world into several years of severe anomalous weather. Such events happen globally about every 10 000 years (Self 2006), perhaps sufficiently frequently to be taken seriously. The phenomena, environmental effects and global consequences of large magnitude explosive eruptions are summarized in the contributions of Lowenstern *et al.* (2006) and Self (2006). A working group of the Geological Society of London, also supported by the International Association of Volcanology and Chemistry of the Earth's Interior, has produced a report on supervolcanoes (www.geolsoc.org), which is aimed at opinion-formers and decision-makers.

For volcanic eruptions, the nature and state of the science is quite different than NEOs and it is less clear what can be done. Only *ca* 20% of the world's volcanoes with potential for explosive eruption have records that extend back over 10 000 years (Deligne & Sparks in review). Statistical studies of the global database suggest that for volcanism more than 2000 years ago, only 20% of large magnitude explosive eruptions have been recognized. Much work needs to be done to improve the basic record and identify high-risk areas. It is likely that several locations with potential for future super-eruptions have not yet even been recognized. A particularly thorny problem is that even if a large volcano shows signs of an impending eruption, we do not know how to recognize whether it will turn out to be a much more commonplace small eruption or a very rare super-eruption (Lowenstern *et al.* 2006). Much more research is also needed to evaluate environmental effects and validate these assessments from geological data. Most importantly no known technology can prevent volcanic eruptions.

Although other natural hazards may not have direct global effects, a large earthquake, tsunami, giant landslide, tropical cyclone or flood in the wrong place at the wrong time can have serious global repercussions. Stein *et al.* (2006) illustrates this issue by an analysis of a major earthquake beneath Tokyo. This study suggests that there is a 40% chance of such an earthquake in the next 30 years and the economic losses, estimated at many billions of dollars, might plunge the world into financial crisis. Earthquakes affecting Istanbul or Tehran (Jackson 2006) or an eruption of Vesuvius affecting Naples, might have a variety of political, social and economic consequences that go well beyond the borders of the directly affected nations. A large landslide of the flanks of a volcano or continental shelf may result in ocean-wide tsunamis. This controversial topic is discussed in more detail by Masson *et al.* (2006) and McGuire (2006).

A particular difficulty with extreme events is that by definition they happen infrequently. Communities tend to be better prepared to adapt to the higher frequency hazards, for which communities hold their collective memories of previous disasters. Populations prone to frequent tropical cyclones build shelters, whereas those in earthquake zones may design buildings that can withstand shaking. In Bangladesh, mounds and purpose-built shelters are built to protect the population from frequent floods related to storm surges. In 1970, a storm-surge flood generated by a tropical cyclone killed an estimated 300 000 people in Bangladesh. Since then, several similar events have resulted in only a few hundred deaths as a consequence of the mitigation steps of building shelters on mounds. Without wishing to underplay that loss of life still occurs, the dramatic reduction in deaths is impressive. However, in many instances designs are typically made for more frequent events of lesser magnitude or building standards fall short of design criteria. For large magnitude events that happen less frequently than once every few generations, the preparations may not be sufficient. The estimated death toll of 938 during Hurricane Katrina is large for a highly developed country and was a consequence of the effects being more severe than had been planned for.

4. Identifying areas at risk

A sensible approach to identifying areas at risk is to use historical information combined with scientific understanding in order to map out hazard-prone areas. This approach is the basis of a recent study sponsored by the World Bank (Dilley *et al.* 2005; Dilley 2006). This works for reasonably frequent and persistent hazards, but is of limited value for rare and extreme events. The historic catalogue, and in particular the 20 year period of analysis in this study, is not long enough to be adequately representative. In some cases, areas with high risk could be missed. It is, for example, a moot point whether the threat of tsunamis on coastal Sri Lanka would have been recognized by such desk-based retrospective studies prior to 26 December 2004 and, depending on the length of the record used, and the same problem may be true for other regions.

One of the most frustrating aspects of the Asian tsunami is that the science was sufficiently well-known for the tragedy to have been anticipated well before it happened. Maps of earthquake hazard published in 1987 and 1996 (McCann *et al.* 1979) identified the Sumatran plate boundary (Sieh 2006) as a place that had accumulated large strains over a long length. Sumatra was identified as one of the two places on Earth where a magnitude 9 earthquake might occur in the near future; Peru was the other identified locality. The basic principles of tsunami propagation and behaviour have been understood for decades and the high likelihood of tsunamis accompanying ocean floor earthquakes greater than 8.5 was also well known. Geologists such as Sieh (2006) recognized the signs of an impending huge earthquake. They based their conclusion from the sinking of islands to the south of Sumatra due to the inexorable bending of the plate. Sieh and colleagues were so concerned that they distributed leaflets to Indonesian citizens on what to do if there was an earthquake. As documented in the report of the UK's Working Group on Natural Hazard (DTI/Pub 7874/1k/06/05/NP.URN 05/1260), the science was known, but the mechanisms to communicate this science to those who needed to know was inadequate.

Hurricane Katrina is even more problematic. Such an event was foreseen in a Scientific American article (Fischetti 2001). In this case, forecasts of the track were accurate and gave three days warning to authorities in New Orleans (McCallum & Heming 2006). In terms of storm track, the science was not only known and robust, but was communicated. However, the storm surges, intensity and resulting devastation were not well forecast.

A major lesson from extreme natural events is that a better job needs to be done to identify systematically areas at risk and to establish more effective ways to communicate with authorities and communities likely to be affected. The first task is easily achievable if enough resources are made available. As an example, it is straightforward to recognize major fault zones that have not ruptured recently, and therefore the region may be at high risk (see Jackson 2006; Kanamori 2006). It is currently impossible to predict (*sensu stricto*) with any confidence the magnitude, and timing, of the eventual failures, but high-risk areas can be identified, and steps can be taken to mitigate the effects before the earthquake happens. In the next few decades, Earth scientists are not going to be surprised by large earthquakes that effect Istanbul, Tehran, Toyko, a number of cities in northern India and the Pacific Northwest. Sieh (2006) provides compelling evidence that very large magnitude earthquakes are imminent in the south of Sumatra along the plate boundary to the east of the fault system that failed in 26 December 2004. When these earthquakes occur, the south of Sumatra will be again devastated, and tsunamis may well reach northern Australia. A systematic inventory of high-risk regions needs urgently to be collated. This inventory cannot be achieved successfully only by retrospective analysis of the inadequately short historical records for extreme rare events, but should use scientific understanding and statistical analysis to identify areas that have not yet been recorded.

5. Prediction, forecasts and warnings

The ability of scientists to predict, give good forecasts and provide timely warnings varies greatly between different hazards and in different circumstances. Here, we use prediction in the sense of quite precise statements on the time, place and size of a future event. Forecasts are more general statements about future hazardous events, which are commonly expressed probabilistically (i.e. how likely it is for an event to happen). Effective warning depends not only on science and technology but also on communication systems and on how the messages are interpreted (Basher 2006).

Earthquakes remain the most difficult of the natural hazards to predict and forecast. Areas at risk from earthquakes are mostly well-known and forensic geological and historical studies can identify fault zones that have accumulated strain over long periods of time. However, it is exceedingly difficult to provide predictions on the timing and magnitude of an earthquake. Pessimism about a universal rule for earthquake prediction is widespread among specialists (e.g. Jackson 2004; Kanamori 2006), and may be physically precluded, although there are counter views (Uyeda & Meguro 2004). Misconceptions have also been revealed by the Asian earthquake. For example, senior officials concluded that another very large magnitude earthquake would be unlikely in southeast Asia since the stress built up had been relieved. However, as detailed by Sieh (2006) and Kanamori (2006), large earthquakes are commonly followed by further large earthquakes in neighbouring regions. For example, stress transfer led to another rupture in the Sumatra region on an adjacent segment of the fault in March 2005, triggering a magnitude 8.7 earthquake and a 3 m tsunami. The faults to the southeast of the epicentre of the Sumatran earthquake are still building up stress, and the chances of neighbouring faults also failing become greater not less. Sumatra remains a highly threatened region where investment in preparedness and mitigation may save many lives (Sieh 2006).

So-called ‘false’ alarms are a major problem for many hazards. For volcanic eruptions the difficulty is that it can be hard to distinguish volcanic unrest due to underground magma movements from the signs of an impending eruption (Sparks & Aspinall 2004). Also, we cannot yet predict the size, duration and climax timing of an eruption. Magma movement causes earthquakes, ground deformation, release of volcanic gases and phenomena such as steam explosions. However, magma may fail to erupt. The 1976 crisis at the Soufrière Volcano, Guadeloupe is a *cause celèbre*, when unrest and uncertainty led to the evacuation of 70 000 people for 3 months. No significant magmatic eruption took place. This apparent failure by scientists led to skepticism among some of the local population, which will mean that a future crisis at this volcano may be even harder to manage.

Warning systems for tsunamis are now quite sophisticated and the Pacific Tsunami Warning System (PTWS) has worked well (Bernard *et al.* 2006). Admittedly, there is a problem about too many false alarms, but this problem can be solved in the future. The combinations of technology, good understanding of the propagation of the waves and good communications allow timely warnings. The nature of tsunamis also means that the warnings can be given many tens of minutes, if not hours, before a tsunami arrives (Synolakis & Bernard 2006), except on coastlines close to the epicentre. Warnings are of no use unless the recipients are well-prepared to respond and take action. In this regard, many of the countries within the Pacific system have well-prepared communities and simple steps have been taken to make sure that there is continuous education in coastal communities. All these attributes of a warning system were tragically missing on 26th December 2004.

Extreme weather can also be forecast and effective warnings given (McCallum & Heming 2006). For Hurricane Katrina, however, while the warning came in time, the response was inadequate. A further problem was that the levees were designed for a category 3 surge and no money had been forthcoming to upgrade them. The reasons for this are complex and no doubt are currently being analysed in the aftermath of the disaster, but the essential issues are likely to relate to preparedness and education of public officials and agencies responsible for acting on warnings. Predicting accurately the intensity of extreme weather can be a problem. Assessments may have to be given in probabilistic terms and this can lead to false alarms. Forecasts can be based on multiple calculations (known as ensemble runs) with only a proportion of the calculated predictions crossing some dangerous threshold. For example, if the calculations suggest that there is a 30% chance of extreme weather then the more benign outcomes are more likely. Should an extreme forecast be provided, at what level of probability, and in what form and with what caveats?

6. Preparedness and mitigation of extreme natural events

Recent events show that nations and the international community are not well prepared for rare extreme events. The national and international mechanisms to deal with these problems have evidently not been working adequately. International organizations like the UN have envisaged that nations should take individual responsibility for developing preparedness and mitigation programmes and initiatives, albeit supported by international activities such as the International Strategy for Disaster Reduction (ISDR). For extreme natural events that affect many countries, however, this approach looks increasingly questionable. A great deal of energy is going into soul-searching and analysis following the Asian tsunami and Hurricane Katrina. The Hyogo agreement and the report of the UK Working Group on Natural Hazards are examples of the response. Suggestions for change include the formation of an International Science Panel for Natural Hazard Assessment, a wider remit for the World Meteorological Organization in distributing warnings, the creation of a global early warning system for tsunamis and a major role for the Global

Earth Observing System programme (www.noaa.gov/eos.html) in assessing natural hazards. UNDP and the World Bank are also currently exploring a new programme for assessing global risks from natural hazards.

A major emerging issue is who is responsible for the transfer of scientific knowledge and technical know-how to those who need to know, as discussed by Shah (2006). We offer here a perspective that does not seem to have been widely discussed. Application of scientific research usually relies on the existence of an effective market alongside demand from concerned stakeholders or users who need the products of research. In many cases, scientists do the research that is then delivered to private industry to develop into products and the market. Commonly governments assist by various mechanisms. In other cases, government or government establishments are the customer of science research and do their own research in government laboratories. Government agencies then do the development to practical application, such as informing environmental regulations, developing new treatments in public hospitals or military devices. The path from science-based research through to application or product is usually clear and is demand led, although rarely simply implemented. We suggest that this path is not so clear for natural hazards; a problem characterized as 'the last Mile' by Shah (2006).

The issue then for natural hazards is: who is responsible for bringing the results of science research and technology to the communities and authorities that need this knowledge for mitigation and preparedness? Put another way, where is the demand for hazards related research? The insurance industry is perhaps the only major industry with direct interest in these issues and here the market clearly plays a central role (Smolka 2006). Until now, insurance, or the sharing of risk, is only widespread in the developed world, so that industry can only play a partial role. Politicians and civilian authorities are a major potential customer for the results of research on natural hazards for the good of their citizens. However, the costs of application, in practice, are prohibitive for many low to medium income countries and may have very low priority in comparison to poverty alleviation, economic development, education and health, for example. An important role in knowledge and technology transfer can be played by NGOs, development banks, and public private partnerships The role of individual nations is also problematic for events that affect many countries; regional and international organizations may not give natural hazards sufficiently high priority. Almost inevitably natural hazards become a priority immediately after a major disaster, with spending on disaster relief being vastly greater than spending on mitigation. As one example, the European Commission Humanitarian Office currently spends half a billion Euros per year on response, relief and recovery and less than ten million on preparedness. The tendency for taking short-term perspectives is endemic in politics and government. The media are another potential customer who can play a positive role in education and communication about hazards and risk. Responsible journalism provides a very powerful mechanism for persuading politicians to act and communities to take notice of scientific information. Regrettably, the media can also be sensationalist and only become interested in natural hazards when death and destruction have already occurred.

Perhaps the demand that really matters is generated from the bottom by ordinary people, who are threatened by natural hazards. Education has a key role in producing citizens and specialists in the affected countries who are well-informed and part of the connected international community that understands the technical advances and how to apply them. In developing countries innovative schemes for education, self-help and access to knowledge, such as the Knowledge Centre concept in India (Kesavan & Swaminathan 2006) can play a critical role. It appears that too few resources are invested in education on natural hazards in long-term educational projects that build up knowledge, understanding and ultimately demand in local communities as well as indigenous expertize that can offer effective advice to authorities.

Another psychological difficulty is that it is always much harder to justify spending money on steps that lead to loss avoidance and prevent loss of life than to spend it on the visible effects of disaster. The PTWS is a good example of international cooperation in a region, but also illustrates some of the problems in guaranteeing long-term support for monitoring. Despite its success, the PTWS was under threat of closure (Bernard *et al.* 2006) and appears to have been only saved by the Asian Tsunami. Stories of failure in natural disasters are typically far more prominent than examples of success, especially in the media. One example of an outstanding success for science occurred in the 1991 eruption of Mount Pinatubo. Here, one of the largest and potentially most devastating explosive eruptions of the twentieth century occurred on 15th June 1991. The dynamics of the volcano was poorly known, having had its last eruption 600 years previously. The Philippine Institute of Volcanology with the assistance of the Volcanic Disaster Assistance Programme (VDAP) of the US Geological Survey rapidly set up a monitoring network and over 300 000 people were evacuated a few days before the eruption. There were only 300 deaths. Without the foresight of the scientists involved this could have been one of the greatest disasters of the twentieth century in terms of loss of life. These unsung scientific heroes have never been widely recognized and there were no headlines or CNN broadcasts with the headline ‘scientists prevent cataclysm’.

7. Concluding remarks

The effects of natural hazards are inexorably increasing and have to be seen in the context of an increasingly complex, interdependent and populated world. The increase is largely the consequence of growing vulnerability exacerbated by human activities, but for some hazards there may be a real increase due to climate change and associated sea-level rise. Globalization also means that the consequences of natural events are increasingly penetrating beyond the borders of the nation that is directly affected. If the disaster is in a poor country then the international community responds mostly with disaster relief. If the disaster is in a developed nation, such as the USA or Japan, then there can be adverse effects for the whole world economy, with major financial and human losses. Some disasters are on such a large scale that they affect many nations and may even have global effects and repercussions. It seems that while there have been and continue to be significant scientific advances in our understanding of natural hazards, the application of the science and the response mechanisms have been inadequate. As eloquently expressed by Shah (2006) we need to ‘travel the last mile’.

There is always more research to be done; this is endless and, with finite resources and many other priorities for governments, the research community cannot expect a huge increase in research funding. Responses to natural disasters are largely after the event and not enough is being done to support research to identify areas at risk, assess this risk, recommend countermeasures and strengthen resilience in communities at risk. In many areas of science, the application of scientific research is demand led, but this seems not to be the case for natural hazards. Demand is partial, short-term and typically follows a crisis. Scientists need to be more vociferous both to create demand and to make sure that robust science is prominent in policy-making. It is enormously difficult to get money to protect against a forthcoming event. At the meeting Haresh Shah proposed that for every dollar spent on disaster relief five cents might be put into a fund for preparedness. A scheme of this kind is currently under consideration by the DFID, a Department of the British Government. This idea would greatly benefit from being promulgated internationally, especially while there is an impetus to create an international fund for disaster relief. Finally, we stress the importance of education of people at all levels, from clear advice to communities to advanced education of local providing experts.

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