European Science Foundation

GHCP

GEO Group on Earth Observations

Extreme Geohazards: Reducing the Disaster Risk and Increasing Resilience

A Community Science Position Paper

European Science Foundation (ESF)

The European Science Foundation was established in 1974 to provide a common platform for its Member Organisations – the main research funding and research performing organisations in Europe – to advance European research collaboration and explore new directions for research. ESF provides valuable services to the scientific and academic communities – such as peer review, evaluation, career tracking, conferences, implementation of new research support mechanisms and the hosting of high-level expert boards and committees – with the aim of supporting and driving the future of a globally competitive European Research Area. ESF currently has 66 member organisations in 29 countries.

www.esf.org

Group on Earth Observations (GEO)

The Group on Earth Observations (GEO) is an intergovernmental organisation developing and implementing the Global Earth Observation System of Systems (GEOSS). GEO's vision is a future wherein decisions and actions, for the benefit of humankind, are informed by coordinated, comprehensive and sustained Earth observation and information. GEO has currently 97 Member Countries and is supported by 80 Participating Organisations.

www.earthobservations.org

Geohazard Community of Practice (GHCP)

The GHCP is a Community of Practice (CoP) supporting the Group on Earth Observations (GEO). The GHCP brings together groups and individuals involved in various aspects of geohazards, including research, monitoring and risk assessments, mitigation, and adaptation. The GHCP aims to provide a link between the broad geohazards community of practice and GEO in order to ensure that the needs of this community are taken into account in the development of GEOSS; to facilitate support and participation of this community in the building of GEOSS; and promote the use of GEOSS for geohazards-related applications. The GHCP also provides a communication and coordinating platform for high level policy makers and the broader geohazards community.

www.geohazcop.org

Authors

- **Hans-Peter Plag**
  Climate Change and Sea Level Rise Initiative, Old Dominion University, Norfolk, VA, USA
- **Sean Brocklebank**
  School of Economics, University of Edinburgh, UK
- **Deborah Brosnan**
  One Health Institute, University of California Davis, Davis, CA, USA
- **Paola Campus**
  European Science Foundation, Strasbourg, France
- **Sierd Cloetingh**
  Department of Earth Sciences, Utrecht University, The Netherlands
- **Shelley Jules-Plag**
  Tiwah UG, Rossbach, Germany
- **Seth Stein**
  Department of Earth and Planetary Sciences, Northwestern University, Evanston, IL, USA

This document considers the disaster risk associated with extreme geohazards and addresses the challenges of disaster risk reduction for these low-probability, high-impact events. The paper was supported by the European Science Foundation (ESF). It was initiated at the high-level ESF-COST conference on 'Understanding Extreme Geohazards: The Science of the Disaster Risk Management Cycle' held in November 2011 in Spain (see www.geohazcop.org/workshops/Sant_Feliu_2011). The Declaration on Extreme Geohazards and the Reduction of Disaster Risks, which resulted from this conference is reproduced in Appendix C.

Cover picture:
Bárdabunga volcano, Iceland, 13 September 2014.

© iStock

ISBN: 978-2-36873-197-0

Contents

Forewords 3

Summary of Key Findings 6

Executive Summary 7

Abstract 11

1. Introduction 13

2. Global Disasters and Catastrophes 15

3. Extreme Geohazards 19

3.1 Knowing the Upper End of the Hazard Spectrum 19
3.2 Impacts of Extreme Geohazards and Associated Risks 20
3.3 Earthquakes and Tsunamis 22
3.4 Extreme Weather and Landslides 24
3.5 Bolides 24
3.6 Volcanoes 24
3.7 Comparison of Geohazards and Other Natural Hazards 30

4. Disaster Risk, Resilience, Antifragility and Adaptive Capacity 33

5. Cost–Benefit Analysis of Planning for Extreme Geohazards 37

6. Confronting Disaster Risks for Extreme Geohazards 40

6.1 Governance for Extreme Geohazards 40
6.2 Knowledge Assessments and Research Needs 42
6.3 Monitoring and Early Warning 44

7. Conclusions and Recommendations 48

Acknowledgements 51

Acronyms and Abbreviations 51

References 52

Appendices 59

- Appendix A: Glossary 61
- Appendix B: Overview of Earthquakes in the Last 2,000 Years 62
- Appendix C: Declaration on Extreme Geohazards and the Reduction of Disaster Risks 66

Foreword

In his third letter on sunspots (December, 1612) to Mark Wesler, Galileo Galilei writes “the modern observations deprive all former writers of any authority, since if they had seen what we see, they would have judged as we judge”.

Four hundred years have passed since this letter was written, but today, more than ever, it is vital to continue to observe the Earth and invest our resources and capabilities in the development of new observation systems and tools capable of analysing these data and providing new information.

The Earth is a complex, dynamic system we do not yet fully understand. Our existence on the planet and our vulnerability to natural hazards is controlled by complex mechanisms that are often unstable and difficult to interpret. Observing these mechanisms and their interactions, to allow reconstruction of the past and prediction of the Earth’s future behaviour, should be a priority for every government.

Earth observations (EO) and information – derived from space, airborne, land and marine networks – play an essential role in helping to increase the resilience of societies to natural hazards. The facility to provide decision makers with critical and factual data is needed to drive investments to reduce underlying disaster risk factors and to make society more adaptable to the effects of climate change. By using Earth observation data and information, societies can enhance the resilience of exposed communities to hazards and, more importantly, can improve the response of individuals, urban systems and related infrastructures to extreme events.

The Group on Earth Observations (GEO) is working to expand the use of satellite imagery and surface data to support governments that are developing sustainable development policies and reducing exposure and vulnerability to disaster risks posed by natural and human-induced hazards. The GEO community is developing decision-support tools and applications for the full cycle of disaster management, particularly for developing countries, working in close collaboration with national space agencies through the Committee on Earth Observation Satellites (CEOS) – the space coordination arm of GEO – to help improve all phases of disaster risk management (DRM) on a global basis.

More timely dissemination and use of geospatial information from globally coordinated systems to monitor, predict, assess risk, provide early warning, and mitigate and respond to hazards will help reduce loss of life and property at the local, national and regional level. The disaster risk reduction and management challenges facing the global community increasingly demand broad and timely access to high-quality, integrated and sustained Earth observation data and related information.

Moreover, Earth observations are owned by many entities around the world, and no single country is able to acquire the comprehensive data and tools it needs to inform policy in these critical domains. Specifically, crisis management resulting from high-frequency natural and human-induced extreme events requires capacities that generally cannot be provided by one country alone; effective response requires regional/international collaboration and coordination so that, when such events occur, the flow of data from various countries, as well as the international organisations in which they are represented, works smoothly. This is particularly true in the case of extreme hazards, where the potential effect of an event could have a regional or global impact with dramatic consequences on society.

The treatise contained in this Science Position Paper raises serious questions about how the current and future global population can be better prepared for extreme geohazard events and their potentially calamitous impacts. As this important discussion moves forward, leaders in government, the private sector, civil society, and members of the general public should take into account the essential contribution of Earth observations to these issues and to their eventual outcomes.

Barbara J. Ryan
Secretariat Director,
Group on Earth Observations (GEO)

Foreword

Natural hazards that occur frequently on our dynamic planet are increasingly causing loss of human life and damage to goods and infrastructures at the local, regional and global scale, depending on their intensity. The Science Position Paper *Extreme Geohazards: Reducing the Disaster Risk and Increasing Resilience* analyses the potential effects of low-probability high-impact events, which might cause global disasters and even bring our already stressed global society beyond the limits of sustainability.

The initiative that led to the preparation of this Science Position Paper originated from the high-level research conference 'Understanding Extreme Geohazards: The Science of the Disaster Risk Management Cycle' (Sant Feliu de Guixols, Spain, 27 November–2 December 2011), which was co-sponsored by the European Science Foundation and COST.

The conference gathered a variety of experts, including representatives of international organisations such as the United Nations Educational, Scientific and Cultural Organization (UNESCO), the Integrated Research on Disaster Risk (IRDR), the International Union of Geodesy and Geophysics (IUGG), the United Nations Office for Project Services (UNOPS), the United Nations Development Programme (UNDP), the Group on Earth Observations (GEO), and the Global Earthquake Model (GEM) Foundation. The experts reviewed the understanding of extreme geohazards and the how, why, and when of these events. Examples and forensic analyses were presented for a number of disasters that have occurred in the last decades and caused huge loss of human life and catastrophic damage in different regions of the planet.

In the course of the discussions the experts concurred on the idea of documenting the main existing issues and needs for the future, and identified the Life, Earth and Environmental Sciences (LESC) Unit, working under the auspices of the LESC Standing Committee (now the Scientific Review Group for Life, Earth and Environmental Sciences, SRG-LEE) as the ideal platform to promote this action.

In the course of its preparation and thanks to extensive dissemination at specialised international conferences and meetings (AGU Science Policy Conference 2012, European Geosciences Union 2013, European Geosciences Union 2014, Global Risk Forum 2014, GEORISK 2014) the Science Position Paper has gained the attention and input of other scientific experts, thus further expanding its content and taking the paper well beyond its originally planned Executive Summary format.

The Science Position Paper addresses several types of geohazards, but puts special emphasis on the mounting risk of catastrophic effects on populations and infrastructures should our growing and increasingly interconnected modern society be exposed to a very large volcanic eruption. The paper highlights the urgency of establishing an effective dialogue with international organisations and policy makers in order to develop robust risk management, disaster risk reduction, resilience, and sustainability plans in the coming years and decades. It also underlines the need to develop the methodology to assess the potentially global impacts that a major hazard would have on our modern society, which would provide guidance to reduce vulnerability where possible and increase general resilience in the face of surprise events. It concludes that preparedness requires a global monitoring system that could provide timely warning should such a major hazardous event develop.

Professor Dr Hans-Peter Plag
Professor, Ocean, Earth and Atmospheric Sciences, Director, Mitigation and Adaptation Research Institute (MARI) Old Dominion University, Norfolk, Va, USA

Dr Paola Campus
European Science Foundation (ESF), Senior Science Officer in charge of the Scientific Review Group for Life, Earth and Environmental Sciences

Professor Dr Reinhart Ceulemans
Chair of the ESF Scientific Review Group for Life, Earth and Environmental Sciences, SRG-LEE

I am very pleased that ESF has been able to support the initiating Conference and the subsequent work of the research communities concerned. The Position Paper is very timely and addresses key issues of hazards, resilience and sustainability through the contributions from a range of experts.

I note that Director Ryan introduces her Foreword with a reference to Galileo Galilei's writing on sunspots and related observations. At our current state of development, space and geohazards can heavily jeopardise large communities, communications and resilience. For this reason, our society needs a comprehensive and enhanced monitoring network with associated rapid response system.

The social elements of the challenges involved with Planet Earth have been well outlined in earlier ESF reports, notably in the ESF-COST publication *RESCUE: Responses to Environmental and Societal Challenges for our Unstable Earth.*

This Science Position Paper is not only aligned with the message of RESCUE, but it further elaborates concepts related to the Sustainable Development Goals endorsed at the Rio+20 – United Nations Conference on Sustainable Development.

I have no doubt that this Paper will be of interest to a large number of stakeholders and will generate opportunities for improved collaboration as well as concerted actions in the future.

Martin Hynes
ESF Chief Executive

Summary of Key Findings

- Extreme geohazards have the potential to generate global disasters.
- Recent large earthquakes have illustrated the extent of the destruction that extreme geohazards can inflict on a modern society, particularly through cascading effects and chains of failure.
- Disaster risk reduction (DRR) focuses on the risk associated with relatively frequent hazards with major impacts, while the risk associated with low-probability, high-impact events is not sufficiently considered.
- Threats from low-frequency, high-impact events are grossly underestimated in DRR.
- This is particularly true for volcanic eruptions. So far, modern civilisation has not been exposed to an eruption comparable to the most extreme events that occurred during the Holocene.
- Under today's circumstances, these events are associated with extreme disaster risks, comparable to other possible mega-disasters from extreme droughts, floods, pandemics and asteroid impacts.
- A global volcano-monitoring system is required as a basis for an early warning system to provide timely warnings to mitigate impacts on transportation and food security.
- A cost–benefit analysis shows that on a global basis several billion dollars per year should be invested to significantly reduce the risk associated with extreme volcanic eruptions.
- Efficient DRR will also require a reduction in the vulnerability of infrastructure, an increase of general economic and social resilience, and the development of capabilities to adapt to potentially large long-term changes in environmental conditions.
- A paradigm shift toward integrated DRR and Resilience (D3R) programmes could more aggressively facilitate the public trust, cooperation, and communication needed to adequately prepare for and recover from expected disasters as well as 'Black Swan' disasters (low-probability, high-consequence events that are difficult to predict or prevent).
- In D3R, science does not have the primary goal of reducing uncertainties and prediction errors for hazards, but rather to develop antifragile processes and strengthen resilience through increased social capital.
- An international process is needed to assess repeatedly the global risk associated with extreme hazards, including geohazards, and our preparedness to cope with these high-impact events.
- This process could be an amalgam of the process used by the Intergovernmental Panel on Climate Change, the Quaternary Defense Review carried out by the Department of Defense of the USA, and the Global Risk assessment carried out by the World Economic Forum.
- A model-based global simulation of one or more extreme volcanic eruptions that took place during the Holocene would provide a basis for a realistic assessment of the risk and the identification of potential cascading effects and chains of failure.
- The International Charter on Space and Major Disasters should be extended to cover cases of emerging threats for early warning purposes prior to the occurrence of a disaster.

Executive Summary

Extreme Hazards: Potential Causes of Global Disasters and Catastrophes

Humanity is exposed to a broad ensemble of natural and anthropogenic hazards that could cause global disasters and catastrophes. Efforts in disaster risk reduction are challenged by the nature of such extreme events: they are rare, occur as surprises, and tend to have high impacts. Because they are rare, the serious threat posed by extreme events tends to be underrated. The increasingly complex built environment and global dependencies can lead to domino effects amplifying the direct impacts of the hazards. Global catastrophes caused by extreme natural hazards have the potential to severely impact the global economy, food security and stability. Floods and droughts are major threats that potentially could reach a planetary extent through secondary economic and social impacts. With megacities and crucial industries situated in areas exposed to natural hazards, earthquakes, tsunamis, and volcanic eruptions might cause disasters that could exceed the capacity of the global economy to cope. Addressing the challenges that these rare, high-impact events pose to human life and property is essential for the long-term sustainability of civilisation.

Given the nature of these extreme hazards, most ideas about them are based on indirect evidence; in particular the impacts of the hazards on the environment and on society are difficult to assess with certainty. Risk as conventionally defined – the product of hazard probability, value of assets exposed to the hazard, and the vulnerability of the assets – is hard to assess. When the hazard probability is very low, we lack the knowledge to reliably estimate vulnerabilities, especially from indirect effects, both in the near and far-field of the hazardous event.

While the probabilities of most natural hazards do not change much over time, the sensitivity of the built environment and the embedded socio-economic fabric has changed. Exposure to geohazards has increased dramatically in recent decades and continues to do so. Most of the increasing losses occur during less frequent high-impact events at the upper end of the hazard spectrum. The increasing complexity of societies allows even moderate hazardous events to cause regional and global disasters. Understanding the disaster risk therefore requires a distinction to be made between the event (the occurrence of a hazard) and the processes that are triggered by this event and determine its consequences.

Global Disasters and Catastrophes

Risk assessments for extreme hazards require an understanding of the processes triggered in the complex coupled human–natural system by the events that lead, or do not lead, to X-events that are rare, surprising, and have potentially huge impact on human life. These X-events are outliers outside of the 'normal' region that could lead to 'the collapse of everything'. Increasingly, the complexity of modern life amplifies the impacts of natural hazards. Although we understand the 'how' and 'why' for most natural hazards events (although not necessarily the 'when'), how such hazards lead to X-events is less well-studied and understood. For many natural hazards, the unfolding time is short, but the impact time can be much longer. Events that have a short unfolding time but large total impacts over very long impact times are those that are surprising and difficult to prepare for. Extreme geohazards fall into this class of event.

Extreme Geohazards

Geohazards such as earthquakes, landslides, volcanic eruptions, tsunamis and floods cause significant loss of life and property. Most of these losses occur during high-impact events and these losses are increasing as the number of people who live in areas exposed to such hazards continues to rise. Recent major geohazards are dwarfed by the largest geohazards that occurred several times during the Holocene. If such a mega hazard were to occur today, the resulting disaster impacts would be unparalleled. To increase global resilience and reduce the disasters induced by the occurrence of extreme hazards at an acceptable economic cost requires a solid scientific understanding of the impacts these hazards could have on modern society.

The extreme earthquakes that occurred during the last 2000 years have illustrated the destruction they can inflict (Figure 8), both directly and, through tsunamis, indirectly. The resulting disasters are amplified in areas with poor building infrastructure. As a consequence, the earthquakes with the largest magnitude are not necessarily those that turn out to cause the most fatalities or greatest damage. In general, poor countries that are exposed to the same level of hazards as more developed countries experience a disproportionate number of disasters.

The volcanic eruptions in the last few decades have often resulted in a high ratio of fatalities to the immediately impacted population. All but one of these eruptions were relatively minor and direct impacts were local. For larger volcanic eruptions, volcanic ash and gases can induce large indirect effects that often exceed the direct impacts in the near-field of the volcano. This is illustrated by a number of eruptions that have taken place in the last few hundred years (Figure 12).

Extreme geohazards that occurred throughout the last few thousand years rarely caused major disasters because the population density was low, the built environment was not sprawling into hazardous areas to the same extent as today, and human societies were much less complex than today. Similar extreme events today could cause unparalleled damage on a global scale and worsen the sustainability crisis. Simulation of these extreme hazards under present conditions can help to assess the disaster risk and underline the fact that we have been lucky during the last century.

Large volcanic eruptions have the potential to impact climate, anthropogenic infrastructure and resource supplies on global scale. Under the present conditions of a globally connected civilisation facing food, water and energy scarcity, the largest eruptions during the Holocene would have had major global consequences. Events on the scale of the Toba eruption 74,000 years ago could return humanity to a pre-civilisation state. Volcanic eruptions can have more severe impacts through atmospheric and climate effects and can lead to drastic problems in food and water security, as emphasised by the widespread famine and diseases that were rampant after the Laki 1783 and Tambora 1815 eruptions. Hence extreme volcanic eruptions pose a higher associated risk than all other natural hazards with similar recurrence periods, including asteroid impacts.

During the Holocene, at least seven VEI 7 eruptions took place [VEI: Volcanic Explosivity Index]. All but one occurred at a time when the global population was far below 1 billion; with a population above 7 billion and heading for 12 billion, a recurrence of a VEI 7 eruption could have extreme consequences. The probability of such an event occurring in the 21st century is 5–10%. Consequently, VEI 7 and larger eruptions represent a severe threat for our modern society.

Disaster Risk, Resilience, Antifragility and Adaptive Capacity

With the prospect of the global population reaching 12 billion by 2100, humanity faces the crucial challenge of developing in a very limited time an effective programme to reduce the risk of global disasters and catastrophes caused by natural hazards. Considering risk as the product of hazard probability, sensitivity to the hazard, and the value of the exposed assets, it is obvious that risk mainly can be reduced by reducing sensitivity and exposure. Adaptation and mitigation efforts to reduce sensitivity and exposure represent insurance against the risk. Willingness to engage in adaptation and mitigation depends on risk perception. The challenge of extreme geohazards is that they are infrequent and risk awareness is generally low. Therefore, the costs for adaptation and mitigation are often postponed.

Extreme geohazards have short unfolding times, leaving little room to increase preparedness when an event has started to unfold. Despite the low probability of such extreme events, their risk is increasing due to the increasing complexity of our civilisation. Efforts to be better prepared for extreme events by developing general resilience are urgently needed, and an immediate benefit would be increased preparedness for frequent events that cause an increasing number of fatalities and rapidly escalating damage. General preparedness needs to be developed as part of the design of communities. For hazards with a potentially global extent, the provision of 'lifeboats' should be the aim for our global civilisation, just as a ship should have sufficient lifeboats for the passengers in the event of an emergency. A focus on food and water reserves, technology redundancy, and social community resilience is therefore a prerequisite for any successful global disaster risk reduction strategy.

For a better understanding of how human interactions with extreme hazardous events can increase, or reduce, the impacts, information on the processes that unfold during and after the incidents is needed.

A human observatory needs to be developed that would collect the data needed to understand these processes.

Cost–Benefit Analysis of Planning for Extreme Geohazards

A cost–benefit analysis based upon a Toba-like VEI 8 eruption and assuming that the risk of fatalities could be reduced by 50% if a timely warning were available to allow for rapid preparations shows that humanity should invest in the order of $0.5–3.5 billion per year in volcano monitoring. VEI 8 eruptions have a frequency of 1.4 to 22 events/Ma. Assuming that such an event would kill 10% of the global population, mainly through starvation, this results in a probability of a random person dying in any particular year of between 1.4×10^{-7} and 2.2×10^{-6}. With a 'value of statistical life' (VSL) of $2.22 million, and a population of 7 billion, the risk for fatalities alone is $1.1–7.0 billion per year. This estimate is at the very low end because it only considers the risk of VEI 8 eruptions and neglects those of lower VEI; it uses a low value of VSL; and it does not consider costs of property damage and indirect economic impacts.

The more frequent VEI 7 eruptions also are associated with high risk. With at least seven VEI 7 events during the last 10,000 years, there is a 5–10% chance of a VEI 7 eruption in the 21st Century. The impacts on our modern society could result in a global disaster, and it is timely to take measures to reduce this risk.

Confronting Disaster Risks for Extreme Geohazards

While adaptive management works for slow changes, including climate change and sea level rise, preparing for extreme geohazards requires pre-emptive action to increase preparedness and general resilience. The major geohazards that are experienced frequently present an important opportunity for us to learn from their impact on our increasingly complex society. An antifragile approach provides a foundation for the reduction of global disaster risks.

Risk awareness and monitoring, as well as the capabilities and means to mitigate risk, are highly uneven across the world. As a result, potential hazards are much more closely monitored in wealthy countries than in the developing world, where low risk awareness combined with poverty and corruption can turn a hazardous event more easily into a disaster. However, the largest hazards are global in nature, and efforts need to be made towards a well-developed global monitoring system for geohazards in support of early warnings. An international governance structure is needed to coordinate global risk assessments and, if needed, appropriate responses.

Research focusing on community disaster resilience is in its early stages. Simulation of selected extreme hazards under present conditions can help to identify weaknesses in the global socio-economic system that could lead to cascading effects. Essential variables to be monitored by a human observatory need to be identified. Research on the response of our global community to a warning that an extreme hazard is developing is limited and efforts need to be made to understand the impacts of such a warning on global stability and preparedness.

Although significant efforts have been made to coordinate global Earth observations (for example through the efforts of the Group on Earth Observations, GEO), a comprehensive monitoring 'system of systems' that could give timely warning for an impending extreme volcanic eruption is not in place. A monitoring system should combine surface displacements, gravity changes, seismicity, chemical variables, and infrasound to detect emerging volcanic eruptions and assess their potential magnitude ahead of the main eruption.

Conclusions and Recommendations

Humanity is poorly prepared to meet the challenge of extreme geohazards. In particular, a large volcanic eruption (VEI 7 or larger) would challenge modern society to the core. Reasons for not being prepared include low perceived likelihood, low political sensitivity, a disconnect between the scientific communities and decision-makers, the lack of socially acceptable strategies including the cost of making preparations, and a common belief that the consequences would be so extreme that preparedness is futile. To overcome these issues, a better process for understanding the available scientific knowledge and using it in proactive decision-making needs to be developed.

Several elements are needed to address the global risk from extreme geohazards:

- A global scientific framework for strategic extreme geohazards science in support of warnings, preparedness, mitigation and response to be implemented by governments, communities and the private sector on a global scale to minimise the impacts of extreme geohazards;
- Scenario contingency planning to better understand the threats and reduce the risk particularly

by reducing systemic weaknesses that could lead to cascading effects;
- Improved risk awareness through dissemination of information on the risk associated with extreme geohazards;
- A global monitoring system to provide early warning for emerging extreme volcanic eruptions;
- An informed global governance system capable of responding to emerging global threats and coordinating measures to increase preparedness and general resilience with the goal of reducing the global disaster risk.

As an immediate step, the existing International Charter on Space and Major Disasters should be extended to include actions aimed at increasing preparedness and to cover cases of emerging threats for early warning purposes.

Abstract

During the Holocene, the most recent geological epoch that started 11,700 years ago, extreme geohazards occurred that were much larger than those experienced during the last century. These events rarely caused major disasters because compared to today population density was low, the built environment did not sprawl into hazardous areas, and the complexity of human societies was much lower. Our modern, globally interconnected society would be extremely challenged if it were exposed to such hazards today. Even some of the large events that occurred a few hundred years ago could cause unparalleled damage on a global scale and worsen the sustainability crisis.

Extreme hazards – rare, high-impact events – pose a serious and underestimated threat to humanity. The extremes of the broad ensemble of natural and anthropogenic hazards can lead to global disasters and catastrophes. Because they are rare and modern society lacks experience with them, they tend to be ignored in disaster risk management. While the probabilities of most natural hazards do not change much over time, the sensitivity of the built environment and the vulnerability of the embedded socio-economic fabric have increased rapidly. Exposure to geohazards has increased dramatically in recent decades and continues to do so. In particular, growing urban environments – including megacities – are in harm's way. Because of the increasing complexity of modern society even moderate hazards can cause regional and global disasters.

Among geohazards (volcanic eruptions, earthquakes, tsunamis, landslides, floods, droughts, and bolides), large volcanic eruptions pose the most severe threat. Under the present conditions of a globally connected civilisation facing food, water and energy scarcity, the largest eruptions during the Holocene would today have major global consequences. Events like the Toba eruption about 75,000 years ago could return humanity to a pre-civilisation state. Atmospheric and climatic effects of volcanic eruptions could lead to severe problems for food and water security, causing large numbers of fatalities. Cascading effects resulting from disruptions of supply chains could cause a global economic crisis.

Potential hazards are much more closely monitored in wealthy countries than in the developing world. Because the largest hazards are global in nature, it is critical to get as much forewarning as possible to formulate an effective response. For this reason, a well-developed global monitoring system for geohazards is needed, not least to support the early detection of extreme hazards.

In addition to the hazards, disaster risk reduction strategies also need to focus on the processes that lead from a hazardous event to the disaster. The understanding of how to reduce the complexity that facilitates these processes and to increase community disaster resilience is still in its infancy. Resilience strongly depends on social capital, and building social capital that creates resilience needs to be a key element in disaster risk reduction. To support this, a socio-ecological observation system needs to be designed and implemented.

A first-order cost-benefit analysis shows that for a reduction in the disaster risk associated with large volcanic eruptions, humanity should be willing to invest in the order of $0.5 billion per year.

Several elements are needed to reduce the global risk associated with extreme geohazards:

- a global scientific framework for strategic extreme geohazards science in support of warnings, preparedness, mitigation and response to minimise the impacts of extreme geohazards;
- scenario contingency planning to create the knowledge needed to reduce the risk by addressing systemic weaknesses that could lead to cascading effects;
- increase of risk awareness through dissemination of information on the global risk associated with extreme geohazards;
- a global monitoring system to provide early warning for emerging extreme volcanic eruptions;
- an informed global governance system capable of responding to emerging global threats and coordinating measures to increase preparedness and general resilience with the goal of reducing the global disaster risk.

As an immediate step, the existing International Charter on Space and Major Disasters should be extended to include actions aimed at increasing preparedness and awareness of emerging threats for early warning purposes.

1. Introduction

Our modern society is frequently exposed to geohazards, including earthquakes, landslides, tsunamis, volcanic eruptions, floods, droughts and bolides. As a consequence of these events, humanity is experiencing increasing loss of life and property. During the Holocene, the most recent geological epoch that started 11,700 years ago, extreme events occurred that exceeded by far the events known to us from experience. The occurrence of any of these events today has the potential to trigger global disasters in a globally interconnected and interdependent society. Our dependency on the availability of services such as power, communication, the internet and transportation, and the dependency of other services such as food, water, sewage, and health on these services would amplify the impact of extreme hazards compared to their effects in earlier times. The probability of any such event happening in this century is low but is far from zero, and the extreme risk associated with these hazards requires a thorough understanding of the potential impacts to inform efforts in disaster risk reduction (DRR).

Humanity is exposed to a broad ensemble of natural and anthropogenic hazards that could cause global disasters and catastrophes (e.g. Bostrum, 2002; Smil, 2008). Efforts in disaster risk reduction are challenged by the nature of such extreme events: they are rare, occur as surprises, and tend to have high impacts. Because they are rare and outside of the normal experience, knowledge is limited about when, how, and why they occur, and there is a tendency to underestimate their frequency (Hempsell, 2004b; Wong, 2014).

A major focus in natural hazards research has been on characterising the hazards and understanding the processes that cause them. Most ideas about extreme hazards are based on indirect evidence, and in most cases the record of extreme events is incomplete. For example, about 45 of the largest volcanic eruptions during the last 36 million years (Ma) are known, but the actual number could be much larger (Mason *et al.*, 2004). As a consequence, the frequency and associated risk of these events may be underestimated. The impacts of extreme hazards on the environment and modern society are difficult to assess with certainty, especially those from indirect effects, both in the near- and far-field. Because the probability of these events is low, risk as conventionally defined – the product of hazard probability, sensitivity of the assets, and value of assets exposed to the hazard – is hard to quantify.

Extreme natural hazards add to humanity's sustainability crisis and could push countries, regions, and even the global community outside the boundaries of humanity's safe operating space. Addressing the challenge that these rare, high-impact events pose to life and property is essential for the long-term sustainability of modern civilisation. Recent events such as Hurricanes Katrina in 2005 and Sandy in 2012, the 2004 tsunami in the Indian Ocean caused by the Sumatra-Andaman earthquake, the 2011 tsunami generated by the Tohoku earthquake, and Typhoon Haiyan in 2013 illustrate both that the risks associated with extreme events are difficult to estimate (Stein & Stein, 2014) and that procedures for reducing the disaster risk and mitigating the resulting losses are inadequate. This is even more so for less frequent and more extreme events that could occur at any time.

The global and long-lasting societal and economic impacts of the recent major events triggered by earthquakes, tsunamis, volcanic eruptions, tropical cyclones, floods, droughts and heat waves illustrate the scale of disasters that can be caused by natural hazards, and the challenge of extreme events for disaster risk management. During the past centuries, losses have been increasing, mainly because more people and infrastructure are exposed to these hazards. Most of these losses occur during infrequent high-impact events. Major disasters caused by natural hazards, which can be loosely defined as those causing more than $100 billion in damage or more than 10,000 fatalities (see Section 2), can have enormous national and even global consequences. Such disasters will become more common as populations at risk grow and more of the built environment, including potentially dangerous or crucial infrastructure, sprawls into hazardous areas.

Disturbingly, the recent major natural hazards that caused disasters with global impacts are dwarfed by the largest hazards that occurred infrequently during the Holocene and earlier. The potential impact on civilisation of such rare events tends to be ignored in planning land use, crucial infrastructure and services, and socio-economic processes. One reason for this is the low probability of these events. However, the main reason may be that major past volcanic eruptions, earthquakes, and tsunamis, occurred when exposure of life and property to these hazards was far less than today and the complexity and global connectivity of societies was much lower. Although these events caused disasters that were extreme for the impacted communities, the scale of the disasters was small compared to the damage that similar events would inflict on today's global civilisation.

A fundamental difficulty for assessing the risks of global disasters is that any specific event is rare, making it difficult to predict its occurrence and to determine an appropriate and sensible level of resources to expend defending against it, given other demands on resources. However, extreme geohazards comparable to some of those witnessed in the past can occur at any time. Today, some of those events would cause global disasters and challenge the global community to an extent that is outside the experience of modern society. Therefore, addressing the risk of global disasters caused by low-probability, high-impact hazards is crucial. However, societies have not adopted a systematic approach to the problem, and instead rely on various policies, many of which are turning out to be inadequate even for much smaller events.

A systematic approach to the understanding of the disaster risk resulting from extreme hazards and developing approaches to the reduction of this risk needs to consider a range of issues. These include but are not limited to:

1. What is the problem and what are we trying to accomplish?
2. What do we know and not know?
3. What strategies are available to achieve our goals?
4. What are the costs and benefits of each of these strategies?
5. What is the optimal strategy given various assumptions and the uncertainty involved?
6. What societal and governance processes could facilitate disaster risk reduction?

The first issue is addressed in Section 2, where the terminology to characterise global risks and the societal goals associated with global risk reduction is introduced. The second question is addressed in Section 3. Section 4 explores approaches to reduce the vulnerability of modern society to extreme geohazards. Section 5 shows a generic cost-benefit analysis for measures that would reduce the potential risk for global disasters resulting from extreme geohazards. Section 6 uses the analysis of Section 5 to develop research, monitoring and governance strategies aiming to address and reduce risk from extreme geohazards on a global level. Finally, Section 7 summarises the conclusions and presents core recommendations.

2.

Global Disasters and Catastrophes

Casti (2012) defines 'X-events' as events that are rare, surprising, and have potentially huge impacts on human life. X-events are outliers that are found outside the 'normal' region and could lead to 'the collapse of everything'. Casti points out that scientific studies mainly focus on the normal region, whereas X-events do not lend themselves easily to scientific studies. As a result, much less is known about when, how, and why these events occur. Casti focuses on X-events caused by humans, and concludes that their increased occurrence results from "the exponentially increasing levels of complexity necessary to preserve the critical infrastructure of modern life."

The recent rise in disasters caused by geohazards has similar aspects: increasingly, the complexity of modern life amplifies the impacts of geohazards. Although significant progress has been made in understanding the 'how' and 'why', for most of the more frequent geohazards the 'when' is less well understood (Wong, 2014). How such hazards lead to X-events is even less studied and understood. A X-event triggered by a geohazard results from the interaction of the hazard with the exposed, complex system of a modern society. Risk assessments for extreme hazards need to consider the processes triggered in this complex system by an event that then leads, or does not lead, to a X-event.

For the less frequent high-impact events, the questions of 'how' and 'why' are even less well understood and the frequency of their occurrence is highly uncertain. Risk assessments for extreme hazards are hampered by the fact that probability theory and statistics have limited utility in this context. Although estimates – albeit poor – of the probability of the occurrence of extreme hazards exist, there are almost no data to assess the resulting impacts of such events on a modern society. In recent disasters, unanticipated cascading effects amplified the damage. For example, while the occurrence of Hurricane Katrina in the US in 2005 and the Eyjafjallajökull eruption in Iceland in 2010 were not unexpected, the resulting disasters caused by the interactions of the hazards with the built environment, the services needed by humans, and the social fabric came as a surprise. These events highlighted the extent to which the inherent vulnerabilities of modern society are not understood and that preparedness for a large number of hazards is low.

An important characteristic of X-events is their temporal development. Casti (2012) defines an 'unfolding time' from an event's beginning to its end, an 'impact time' during which the costs or benefits are experienced, and the 'total impact' of the event in terms of costs or fatalities. For natural hazards, it makes sense to distinguish between the hazardous event occurring and the subsequent processes that lead, or do not lead, to disaster. For many geohazards, the unfolding time is short, but the impact time can be much longer. Events with short unfolding times but large total impact over very long impact times can be surprising and difficult to prepare for. Extreme geohazards fall into this class of events.

X-events differ in terms of the disasters they cause. Hempsell (2004a) introduced three categories:

- **Extinction Level Events** are so devastating that more than a quarter of all life on Earth is killed and major species extinction takes place.
- **Global Catastrophes** are events in which more than a quarter of the world's human population dies and that place civilisation at serious risk.
- **Global Disasters** are global scale events in which a few percent of the population dies.

Figure 1. Although the 2004 Sumatra M=9.1 earthquake caused a large number of fatalities (Okal & Synolakis, 2008) and a global shock, this event has a high X-ness only in a relatively small region adjacent to the rupture, where *X* computed on a country basis is close to 1. In most other areas impacted by the tsunami, country-specific values of *X* are small. However, the global scale of the disaster resulted in a large effort to improve tsunami early warning in the Indian Ocean.

In order to include more frequent events experienced in recent history, we introduce a fourth category:

- **Major Disasters** are those exceeding $100 billion in damage and/or causing more than 10,000 fatalities.

Although it is not straightforward to quantitatively assess X-events, a simple equation gives a quantitative indication of the relative importance of an event. Casti (2012) defines:

$$X = \frac{\delta E}{E}\left(1 - \frac{U}{U + I}\right) \qquad (1)$$

where X is the X-ness of an event (a measure of the impact of the event), E the impacted ensemble (e.g. impact on the gross domestic product or the total annual deaths in the impacted region), δE the change in the ensemble due to the event, U the unfolding time of the event, and I the impact time. This equation is used to characterise the X-ness of recent events causing major disasters and to estimate the present-day X-ness of past events. Estimating the unfolding and impact time may be difficult in some cases. In the case of disasters caused by geohazards, we consider the unfolding time as the time between the point when the first signs of a developing hazardous event could have been noticed and the point in time of the full development of the disaster. The impact time is the time it takes for the impacted community to return to a level comparable to that before the event occurred. For an earthquake, unfolding times are often short, although in the case of the 2010 Port-au-Prince earthquake in Haiti, subsequent events (including epidemics) prolonged the development of the full disaster beyond the direct impacts of the earthquake. Estimating impact time also is challenging, particularly in cases where communities do not return to a situation similar to that which was in place prior to the event. An example is the decision in Japan after the 2011 Tohoku earthquake to shut down nuclear power plants for a prolonged period. Estimating the impacted population can be challenging, too. In the case of the 2010 eruption of Eyjafjallajökull, the indirect economic impacts were extremely widespread, and in most cases it is preferable to focus on the direct impacts associated with threats to life.

The relative importance of disasters is poorly expressed by the number of deaths or the damage caused by the event. For example, the 2004 Sumatra-Andaman earthquake caused an ocean-wide tsunami, which impacted most countries around the Indian Ocean to some extent (Okal & Synolakis, 2008), but the highest relative impact was felt in Aceh, Indonesia (Figure 1), where between 3% and 4% of the total population died (Figure 6). The 2008 Burma cyclone, which caused more than 100,000 deaths, killed less than 1% of the people in the impacted area (Figure 6). For the 2010 Haiti earthquake (Figure 2), the number of deaths is uncertain with estimates ranging from 85,000 to more than 300,000, which represents 5–15% of the approximately two million inhabitants of Port-au-Prince and its immediate surroundings. The 2010 volcanic eruption in Iceland was a minor volcanic event (Figure 3), but the interactions of the ash cloud with air traffic caused significant economic damage (of the order of US$2–5 billion; Daniell, 2011) resulting in a relatively high X-ness compared to the magnitude of the hazardous event. On the other hand, the M=8.8 earthquake in Chile in 2010 (Figure 4) has a very low X-ness because the number of fatalities was low compared to the impacted population. The M=9.0 earthquake off the coast of Japan exceeded the maximum magnitude 8 assumed in hazard planning, which resulted in a number of

Figure 2. The 2010 M=7.1 earthquake in Haiti has a high X-ness, independent of whether the fatalities or the economic loss are the ensemble considered.

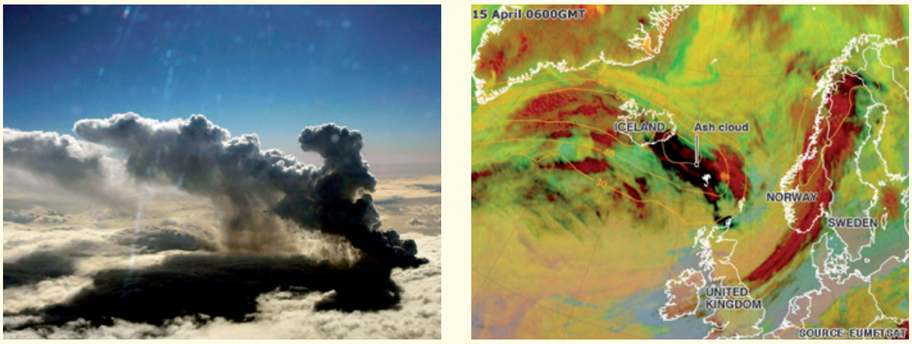


Figure 3. The relatively minor eruption of Eyjafjallajökull in Iceland in 2010 turned into an economic X-event through interaction of the ash cloud with the complex air traffic system in Europe. In the aftermath of the economic disaster, efforts are being made to improve resilience of the air traffic system.

Figure 4. The 2010 M=8.8 earthquake in Chile has a very low X-ness, which to a large extent is due to the use of scientific knowledge of the probability density functions of seismic hazards as a basis for building codes and land use planning.

Figure 5. The 2011 M=9.0 earthquake in Japan has a medium X-ness, mainly because of the domino effects triggered by the tsunami in a region with high complexity and extreme dependency of infrastructure on the functioning of crucial components. Moreover, scientific knowledge of seismic hazards was not sufficiently integrated into the planning of infrastructure, and the scientific knowledge was hampered by false assumptions.

Left: By US Navy photo [Public domain], via Wikimedia Commons.
Right: By US Marine Corps, photo by Lance Cpl. Ethan Johnson [CC-BY-2.0 (http://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons.

Table 1. X-ness of recent major disasters. *U* is unfolding time in hours, *I* is impact time in years, *δE* is number of deaths in the region, and *E* is the total population in the region considered. Hazards are: EQ: earthquake; T: tsunami; C: cyclone.

Region	Hazard	Year	*U*	*I*	*δE*	*E*	*X*
Aceh, Indonesia	EQ,T	2004	2	10	130,000–170,000	4,271,000	0.04–0.05
Pakistan, NW Frontier Province	EQ	2005	15	3	80,000	20,000,000	0.004
Sichuan, China	EQ	2008	15	2	70,000	10,000,000	0.007
Burma	C	2008	30	5	100,000	12,500,000	0.008
Port-au-Prince, Haiti	EQ	2010	120	10	85,000–350,000	2,000,000	0.05–0.17

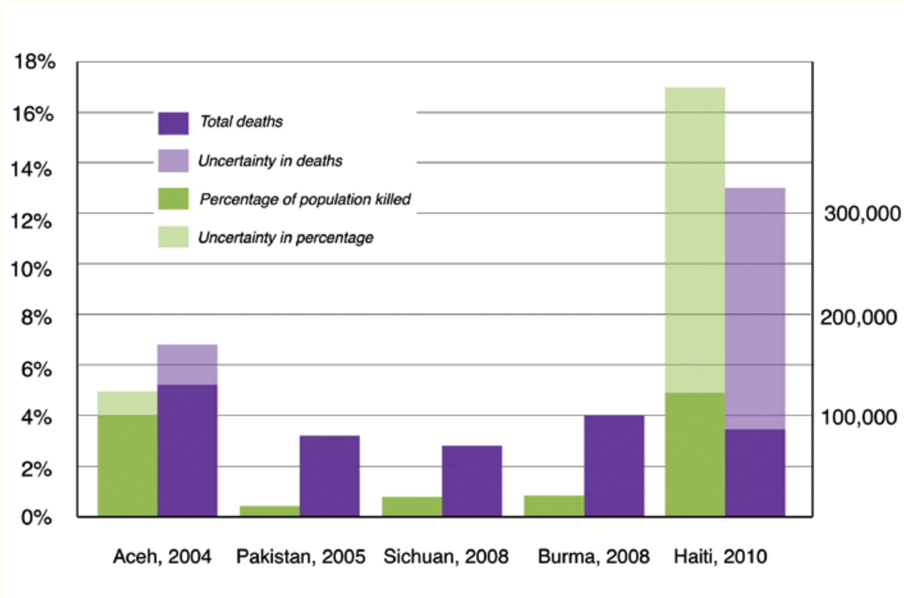


Figure 6. Total death toll of selected recent earthquakes, tsunamis, and cyclones and percentage of local population killed.

cascading effects (Figure 5). In Table 1 and Figure 6, the X-ness of selected events is considered based on the fatalities.

In the context of X-events, 'recurrence interval' is used to refer to the likelihood of an event occurring at least once anywhere on Earth within the given period. Thus, a 500-year flood is the largest flood that typically occurs once within this interval on Earth. A 10,000-year volcanic eruption is the largest eruption that typically occurs within any 10,000-year interval on Earth. The term 'frequency' is used to refer to the average number of events within a given time interval (e.g. a century, 1,000 years, or a million years).

It is important to note that within any given century, assuming a Poisson distribution, the chance that a 100-year event occurs at least once is about 63%. For a 1,000-year or 10,000-year event, this chance is close to 10% and 1% respectively (Table 2). This poses a large challenge for DRR. For example, not accounting for 500-year events in preparation and DRR measures implies ignoring a risk that has an 18% chance of materialising in the next 100 years.

Table 2. Recurrence intervals of events and the chance that at least one event takes place within any given 100 years. We assume a Poisson distribution. *N* is the number of years in which on average one event occurs, i.e. an *N*-year event, *F* is the frequency in a century, i.e. the average number of events per century, and *C* the chance that at least one event occurs in 100 years.

N	*F*	*C* in %
10	10	99.99
100	1	63.21
500	0.2	18.13
1,000	0.1	9.516
10,000	0.01	0.995
100,000	0.001	0.100

3.
Extreme Geohazards

3.1 Knowing the Upper End of the Hazard Spectrum

The recurrence of natural hazards has often impacted human settlements at local and regional scales, causing significant death and loss of property. The most extreme cases have produced very long-lasting impacts on the environment and have dramatically impacted humanity, changing the course of history and bringing humanity to the edge of extinction.

Geohazards considered here include earthquakes, landslides, volcanic eruptions, tsunamis, bolides, and other deformations of the Earth's surface that can lead to damage of property and loss of life, such as sinkholes, subsidence, shrinking and expanding soils, slope instabilities, etc. Floods and droughts are also considered as geohazards because they often cause landslides, erosion, and/or subsidence and surface deformation. Extreme geohazards can cause anything from major disasters to extinction-level events due to direct impacts or other severe conditions triggered by them. Other natural hazards include storms, tropical cyclones, extreme temperatures, and solar storms.

Recent major disasters have highlighted existing gaps in our knowledge of natural hazards and our understanding of the vulnerability of modern society to these hazards. These disasters have also indicated a lack of efficient transfer of the available knowledge to policy and decision making, and a limited use of the knowledge for decision making. In particular, the recent 'extreme' earthquakes that caused significant loss of life and property have raised the question of whether extreme events are accounted for in modern seismic hazard analyses (Wong, 2014) and disaster risk management. A number of earthquakes turned out to by unexpectedly large, such as the 1920 Haiyuan/Gansu, China, the 1960 Chile, and the 2011 Tohoku, Japan, earthquakes. This raises the questions of whether the maximum size and the frequency of these large events are underestimated in risk assessments and as a consequence are not accounted for in risk management. It also raises the question of where the next large but unexpected event might occur.

Understanding the full spectrum of geohazards, including extreme events with consequences from major disasters to global catastrophe, is a prerequisite for effective disaster risk management and increased global resilience to these events. Reducing the disasters induced by the occurrence of extreme hazards at an acceptable economic cost requires a solid scientific understanding of the hazards.

Reviewing the known extreme events of the past and projecting them onto today's sensitivity and exposure of the built environment and the vulnerability of the socio-economic fabric illustrates the risk associated with the low probability, high-impact end of the hazard spectrum. However, to focus solely on the hazards does not consider the full spectrum. It is important to distinguish between the event, that is, the occurrence of a hazard, and the resulting processes that unfold and which may or may not lead to a disaster. Understanding these process requires consideration of the form, functioning, and 'metabolism' of modern societies in order to understand the potential direct and indirect impacts. The high technological level of today's built environment is associated with new vulnerabilities that can amplify the direct impact of a hazard in a chain of triggered failures. These indirect impacts can be more severe than the damage caused directly by the hazards. The state of the social fabric also impacts the process that is triggered by a hazard, and social capital contributes to the scale of the disaster caused by a hazard.

3.2 Impacts of Extreme Geohazards and Associated Risks

For major geohazards, which happen somewhere in the world at least once a decade, the primary risks are to the local population and local infrastructure. These vulnerabilities were highlighted, for example, in the 2011 Tohoku earthquake, Japan, which killed nearly 16,000 people and severely damaged over 400,000 buildings, leading to $122–235 billion in damages (World Bank, 2011). Other estimates resulted in classifying the earthquake as the most expensive earthquake of all time, causing between $400 and $700 billion losses and approximately 19,000 deaths (Vervaeck & Daniell, 2012). Such disasters also have negative effects on the world economy through supply chain disruptions and other cascading (domino) effects, but these are harder to quantify. In an increasingly interconnected and interdependent global society, major hazards can result in significant global economic impacts.

An issue in assessing disasters and trends in disaster risk is the lack of comprehensive databases that allow for the determination of annualised quantities (Muir-Wood, 2012). Tables 3 and 4 compile data extracted from the *International Disaster Database (IDD),* using the tool available at http://www.emdat.be/advanced_search/index.html and the Prevention Web database available at http://www.preventionweb.net/english/professional/statistics/, respectively. Particularly large uncertainties are present in the total damage and the total number of affected people.

During the last few decades, earthquakes have accounted for most fatalities and damage resulting from natural hazards (Table 3 and Figure 7). Earthquakes and volcanic eruptions tend to cause more fatalities among impacted population than floods, droughts and other hazards (Table 4). In terms of affected population, floods are the leading cause with droughts being second. However, the ratio of deaths to affected population is two orders of magnitude smaller for floods than for earthquakes and volcanic eruptions. Hence, the X-ness of earthquakes is generally larger than that of floods and droughts.

The major bolide explosions in the atmosphere or impacts in the recent past (Tunguska, 1908; Sulawesi, 2009; and Chelyabinsk, 2013) affected areas not highly populated. However, their potential for devastation was extremely high. Nevertheless, these events are currently not included in most disaster-related databases.

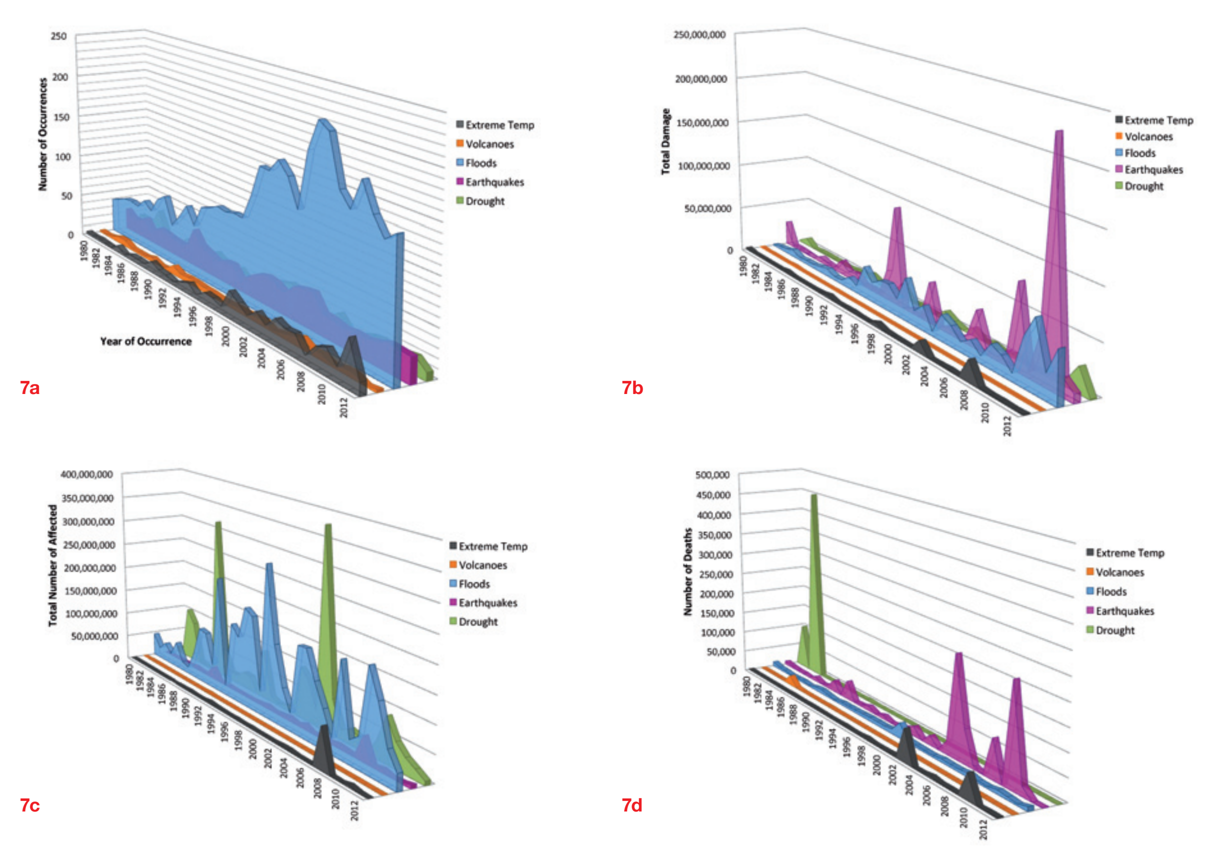
In the context of climate change, extreme weather events are occurring more frequently and across more extended geographical areas. At the local scale, tornadoes, hurricanes and flash floods have large impacts on people and infrastructures. Landslides can also have catastrophic effects at the local scale, and landslide risk is increasing both due to climate change and the impact of land use on land cover.

Although the rate of occurrence of a large or extreme geohazard is not very high, its occurrence in a highly populated region or megacity might cause devastating consequences, as illustrated by the 2004 Sumatra-Andaman and 2011 Tohoku earthquakes and the associated tsunamis. The world's growing population is even more vulnerable to the recurrence of more extreme events that have happened infrequently during the Holocene.

The statistics of a few decades are insufficient to fully understand the potential impacts of low-frequency extreme events on modern society because the probability that extreme events have been captured is low. The relatively poor knowledge of the impact on populations and structures of past geohazards and, in particular, of extreme geohazards, derives from a lack of accurate historical records of such events, thus making it nearly

Table 3. Disaster statistics for the period 1980 to 2013. Data were extracted from the IDD, using the tool available at http://emdat.be/advanced_search/index.html. Damage is in million US $. Hazards are listed according to fatalities. *R* is the ratio of fatalities to the affected population in percent. Note that the figures are reproduced as given in the IDD without rounding. The figures have considerable uncertainties due to missing information or accounting issues. For example, in several years, the number of affected people for heat waves is zero, which means that no numbers were reported.

Hazard	Events	Fatalities	Affected	Damage	*R*
Earthquakes and tsunamis	865	866,882	158,794,738	737,379	0.546
Droughts	499	561,540	1,766,356,773	117,612	0.032
Floods	3,741	229,080	3,277,580,121	619,190	0.007
Extreme temperatures	461	166,921	97,822,633	54,327	0.171
Volcanoes	160	25,539	4,476,906	2,870	0.570



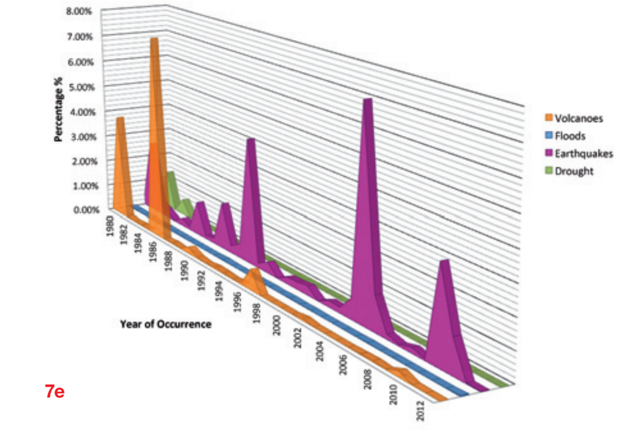


Figure 7. Natural Hazards for the time period between 1980 and 2013. Source is the International Disaster Database accessible through http://www.emdat.be/advanced-search/
7a: Number of occurrences
7b: Total damage in $1,000
7c: Number of affected population
7d: number of deaths
7e: ratio of number of deaths to affected population

Table 4. Detailed disaster statistics for the period 1980 to 2008. Data from http://www.preventionweb.net/english/professional/statistics/. The database is the OFDA/CRED International Disaster Database, maintained by University Catholique de Louvain, Brussels, Belgium. Data version: v11.08. Damage is in million US $. Hazards are ordered according to fatalities. *R* is the ratio of fatalities to the affected population in percent. See Table 3 for a caveat on the accuracy of the numbers.

Hazard	Events	Fatalities	Per year	Affected	Per year	Damage	Per year	*R*
Drought	410	558,565	19,261	1,551,455,122	53,498,452	76,949	2,653	0.036
Cyclone	1,211	402,911	13,893	496,560,639	17,122,781	533,371	18,392	0.081
Earthquake	706	385,630	13,298	136,333,515	4,701,156	351,079	12,106	0.283
Tsunami	18	229,551	7,916	2,481,879	85,582	10,046	0.346	9.249
Flood	2,887	195,843	6,753	2,809,481,489	96,878,672	397,334	13,701	0.007
Heatwave	126	89,889	3,100	4,614,411	159,118	21,990	758	1.948
Volcano	140	25,197	869	4,080,791	140,717	2,871	99	0.617
Landslide	366	20,008	690	7,031,523	242,466	6,060	209	0.285
Cold wave	156	11,595	400	6,875,103	237,073	5,902	204	0.169
Tornado	182	4,780	165	12,710,204	438,283	31,511	1,087	0.038
Avalanche	73	3,532	122	69,637	2,401	807	28	5.072
Wild fire	294	1,666	57	5,766,092	198,831	42,807	1,476	0.029

impossible to extract a realistic estimate of the real damage inflicted to communities and structures. Sometimes these events have become part of the ancestral memories of populations, which allows for qualitative descriptions. Scientists have made efforts to reconstruct the effects of past large and extreme events on populations and environment, using the effects of more recent events during historical times to interpret past events.

In the last two centuries, the planet has dramatically changed: the industrial and technological revolutions have triggered rapid development, promoting communications and progressively increasing the exchange of goods and the rate of travel. Societies are progressively clustering around megacities (United Nations, Department of Economic and Social Affairs, Population Division, 2014), often located in hazardous areas and heavily dependent on fast and efficient transfer of information and people. Most of the decision-making and emergency centres are located in large settlements or megacities, making it crucial to assure the sustainability of such structures to enable timely decisions and support actions at local, regional and global levels under even the worst environmental conditions.

Extreme earthquakes, impacts of large bolides, and volcanic eruptions pose a global threat to a globally inter-connected society that depends on the uninterrupted availability of communication, transportation, power, water, sewage, food, and health services. In the following sections, a review of the potential impacts of major geohazards is provided.

3.3 Earthquakes and Tsunamis

Large to extreme earthquakes during the last 2000 years (see Table 8 in Appendix B) illustrate the destruction they can inflict (Figure 8) directly and indirectly through tsunamis (Figure 9).

The resulting disasters are amplified in areas with poor building infrastructure (Figure 10). As a consequence, the earthquakes with the largest magnitude do not necessarily cause the most fatalities or greatest damage.

In general, poor countries exposed to the same level of hazards as more developed countries experience a disproportionate number of disasters. Poverty, often paired with corruption, can turn hazards into disasters, and the means to increase preparedness and resilience are not sufficiently available in areas with high degrees of poverty.

In addition to shallow off-shore earthquakes, tsunamis can be caused by subaerial and sub-marine landslides, stratovolcanoes located on islands, and by impacts of bolides on oceanic areas or large water bodies. Aerial landslides hitting a limited body of water (such as a lake or a fjord) may generate extremely high tsunami waves, since the water cannot disperse. This was the case for the Lituya Bay, Alaska, tsunami (1958), which reached a maximum height of about 525 meters (Miller, 1960; Fritz *et al.*, 2009) and of the Vajont tsunami (1963), which reached a maximum height of about 250 meters (Panizzo *et al.*, 2005; Zaniboni & Tinti, 2014).

Harbitz *et al.* (2014) show that submarine landslides have occurred along most of the continental

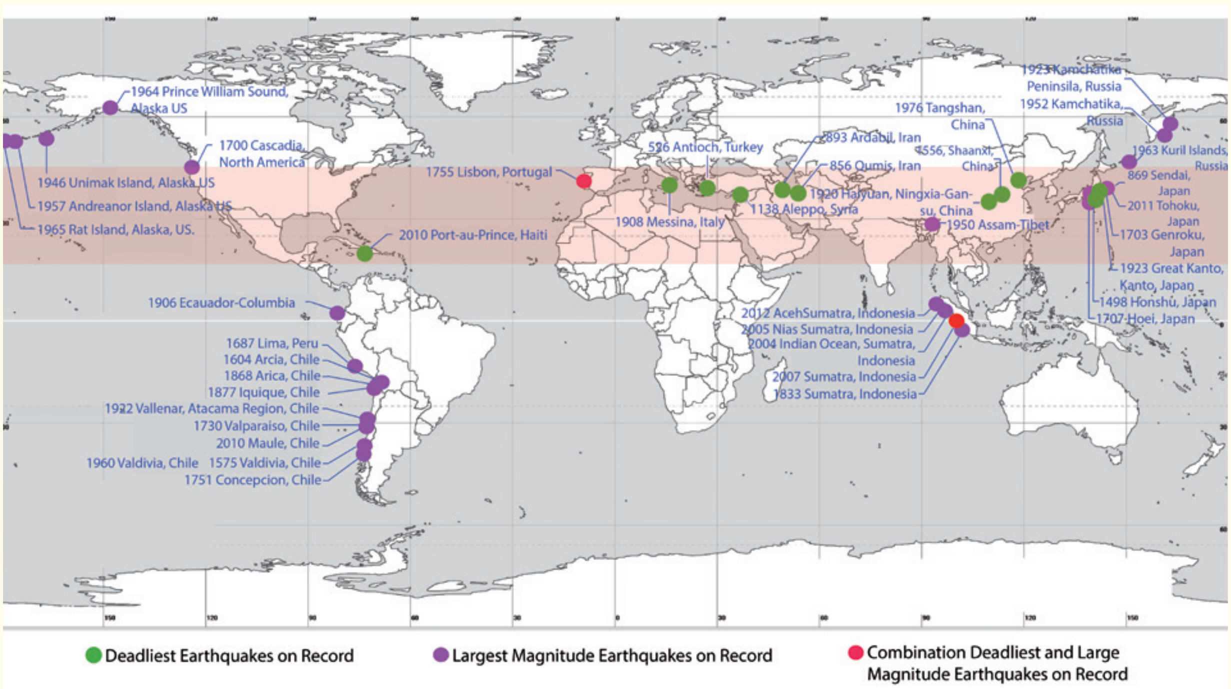


Figure 8. Deadliest great earthquakes on record.

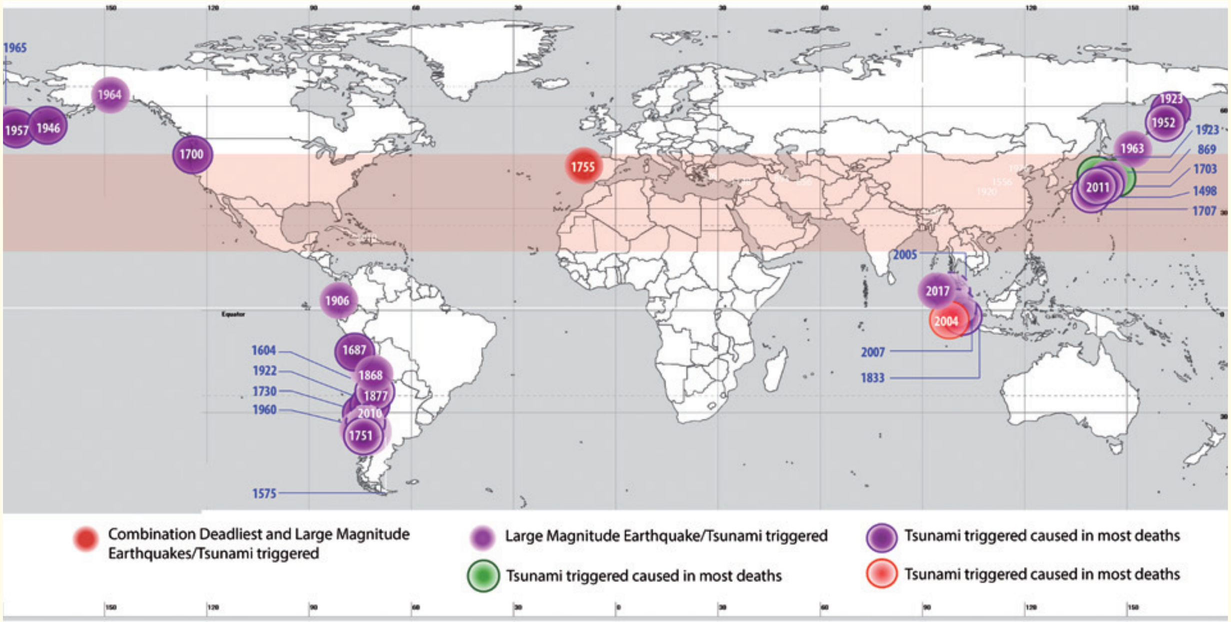


Figure 9. Destruction caused by offshore earthquakes.

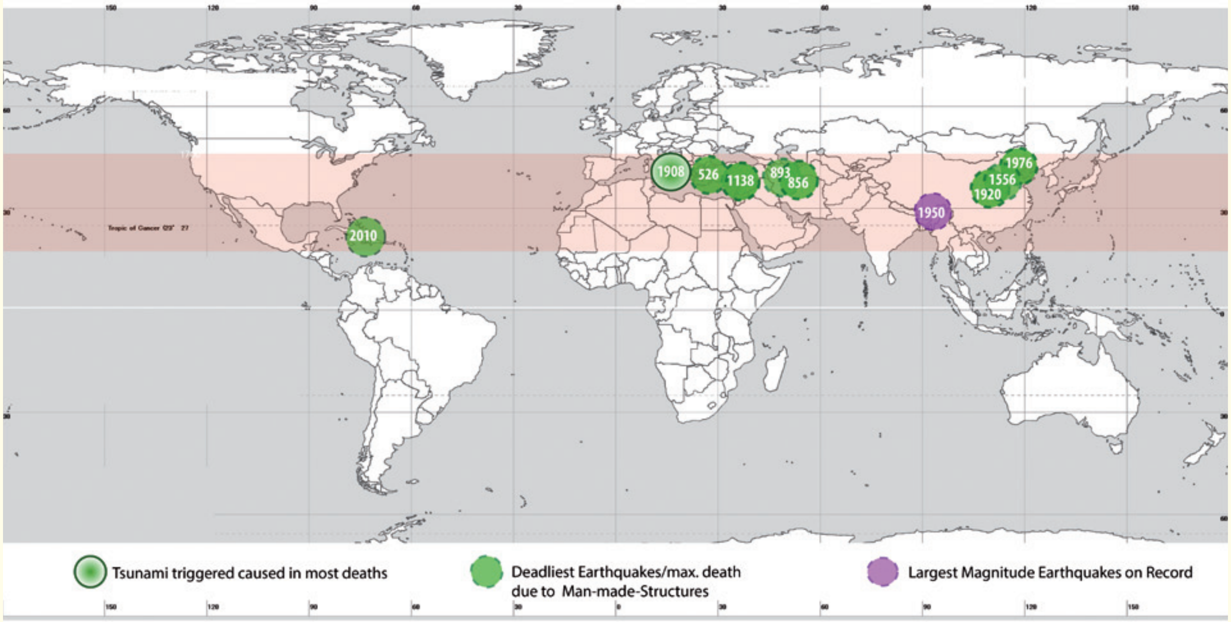


Figure 10. Destruction caused by in-land earthquakes.

margins and several volcano flanks. The physical dimensions, acceleration, maximum velocity, mass discharge, and travel distance are properties of these landslides that determine tsunami generation. The authors conclude that land-slide tsunami characteristics may exceed tsunamis induced by megathrust earthquakes, and hence landslide-generated tsunamis may cause potentially extreme tsunami run-up heights. The tsunami hazard associated with giant submarine landslides related to climate changes and glacial cycles is in most regions negligible compared to earthquake tsunami hazards, although an increase in melting of ice sheets could change this. Large-scale debris flows around active volcanoes or submarine landslides in river deltas may be more frequent. Harbitz *et al.* (2014) highlight that estimation of recurrence intervals, hazards, and uncertainties is still an open question due to a lack of sufficient observations. Although it is estimated that on average bolides large enough to cause a significant tsunami hit the Earth one to two times per century, there have been no recent records of large tsunamis induced by an impact in the oceans or on large water basins.

The design of critical coastal infrastructure is often based on unjustifiably long recurrence intervals for these extreme events. A scenario-based assessment of the tsunami hazard can provide more insight and guidance for the planning of coastal infrastructure. Direct impacts of tsunamis are restricted to coastal zones, while indirect and cascading effects can reach regional and global scales. Mitigation of tsunami impacts is more a local problem, which require local governments to assess the threat, increase awareness and develop resilience plans. Large tsunamis such as those triggered by the May 22, 1960 Chile Earthquake, the March 27, 1964 Alaskan Good Friday earthquake, the December 26, 2004 Sumatra-Andaman earthquake or the March 11, 2011 Tohoku earthquake generated waves which killed people thousands of kilometres away from the epicentre. The catastrophic effects of such tsunamis prompted governments to develop both local resilience plans and to accelerate the establishment of tsunami warning centres across the globe.

3.4 **Extreme Weather and Landslides**

In the context of climate change, extreme weather events are occurring more frequently and in more extended geographical areas. Tornadoes, hurricanes and flash floods have a huge impact at local scales, on both people and infrastructures. Landslides can have also catastrophic effects at the local scale.

3.5 **Bolides**

Bolides have the potential to cause extensive to catastrophic damage, should one hit a densely populated area. Indeed, the impact of a large asteroid could easily result in a global catastrophe or even an extinction level event (e.g. Bostrum, 2002; Hempsell, 2004b; Smil, 2008). The Chicxulub impact crater in the Yucatan Peninsula, Mexico is believed to be the result of a bolide impact that occurred approximately 65.5 million years ago and caused mass extinction (Gulick *et al.*, 2013).

Only in the last century a number of large bolides struck the surface of the Earth, fortunately in areas that were not highly populated. The Tunguska Fireball (June 30, 1908), generated an explosion which flattened over 3000 km^2 of forests, releasing an estimated energy equivalent to more than 1 megaton of TNT (Harkrider, 1964; Ben-Menahem, 1975; Vannucchi *et al.*, 2015). On October 9, 2009 a large bolide hit the Sulawesi region, Indonesia. It has been estimated that the detonation in the atmosphere released an energy equivalent to about 50 kilotons of TNT. On February 15, 2013, a large Earth-impacting fireball disintegrated close to the city of Chelyabinsk, over the Ural Mountains. The blast released an energy estimated around 500 kilotons of TNT (Le Pichon *et al.*, 2013; Gorkavyi *et al.*, 2013; Avramenko *et al.*, 2014) and injured more than 1,000 people due to the effects of the shock wave on buildings.

3.6 **Volcanoes**

Since 1700 AD, volcanic eruptions have killed more than a quarter of a million people and devastated entire communities. Far-reaching effects impacted communities almost on a global scale (see Figures 14 to 16 below). According to some estimates, the population directly at risk from volcanoes in the year 2000 stood at 500 million or more, a figure certain

Table 5. Classification of volcanic eruptions. V: ejecta volume; EC: eruption classification; D: description; PH: plume height; FE: frequency of eruption; O: known/estimated occurrences in the Holocene.

VEI	V	EC	D	PH	FE	O
0	< 10,000 m^3	Hawaiian	Effusive	< 100 m	Persistent	Many
1	> 10,000 m^3	Hawaiian/Strombolian	Gentle	100–1,000 m	Daily	Many
2	> 1,000,000 m^3	Strombolian/Vulcanian	Explosive	1–5 km	Weekly	3,477
3	> 10,000,000 m^3	Vulcanian/Pelean	Severe	315 km	Few months	868
4	> 0.1 km^3	Pelean/Plinian	Cataclysmic	1,025 km	≥1 yr	421
5	> 1 km^3	Plinian	Paroxysmal	2,035 km	≥10 yrs	166
6	> 10 km^3	Plinian/Ultra-Plinian	Colossal	> 30 km	≥ 100 yrs	51
7	> 100 km^3	Ultra-Plinian	Super-colossal	> 40 km	≥ 1,000 yrs	5*
8	> 1,000 km^3	Supervolcanic	Mega-colossal	> 50 km	≥10,000 yrs	0

* plus two suspected.

to grow. This makes it all the more important that scientists develop their capacity to make reliable and timely warnings of eruptions.

Because volcanic eruptions are complex processes that occur in a wide range of settings and forms, measuring their size and hazardousness is not straightforward. Many different scales and indicators have been proposed. A descriptive classification system is summarised in Table 5.

The Volcanic Explosivity Index (VEI) was developed to estimate the climatic impact of volcanic eruption (Newhall & Self, 1982). It uses the volume of the erupted material and the height of the resulting plume to characterise the explosivity of the eruptions (Figure 11). However, the amount of sulfur dioxide gas ejected into the atmosphere, which is not necessarily related to the size of the eruption, is a better indicator of possible climate effects. A problem of the VEI is that it is based on estimated 'bulk volume' without taking into account the density of the deposited material (Mason *et al.*, 2004). To overcome this problem, a logarithmic magnitude scale of eruption size has been defined as $M = \log_{10}(m) - 7.0$, where m is the erupted mass in kg (Pyle, 1995, 2000). This scale has been defined to be close to the VEI.

VEI values have been determined for more than 5,000 eruptions in the Holocene (see Table 6 for examples). None of these reached the maximum VEI of 8. Several of the most devastating eruptions during the last 2,000 years had VEI values lower than 6. For example, the VEI 5 eruption of Vesuvius in 79 AD destroyed Pompeii and Herculaneum. Since 1500, more than 20 eruptions of VEI 5 or more occurred, with only the Tambora eruption in 1815 reaching VEI 7. It is worth noting that the extremely disruptive eruption of Eyjafjallajökull only reached an estimated VEI of between 3 and 4.

The number of fatalities and the amount of damage have also been used to characterise the impact of volcanic eruptions. The size and magnitude of the hazard, i.e. the eruption, is only loosely related to the resulting damage. For example, mudflows triggered by the VEI 3 eruption of Nevado del Ruiz (Colombia) in 1985 caused one of the worst volcanic disaster in the 20th century. As Table 5 shows, of the nine greatest volcanic disasters in terms of casualties since 1500, only three (Tambora, Krakatau and Laki) qualify as 'very large' eruptions with a VEI of greater than 5.

It is worth noting that the VEI 5 eruption of Mount St. Helens in 1980 has a higher VEI than five

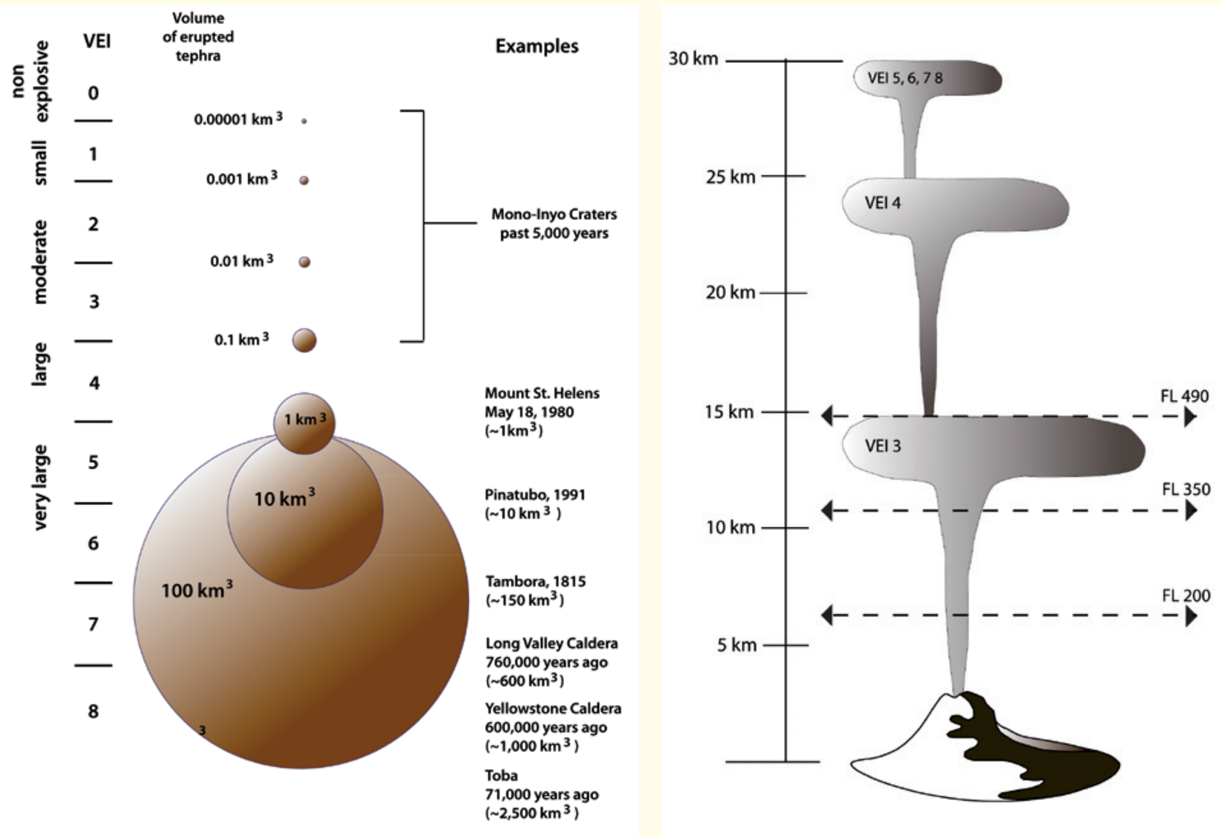


Figure 11. Measures for the magnitude of volcanic eruptions. Several indicators have been proposed to measure the severity of volcanic eruptions. The Volcanic Explosivity Index (VEI) introduced by Newhall & Self (1982) is a semi-logarithmic scale that uses a combination of the volume of the erupted tephra (left) and the eruption plume height (right) to measure the eruption size. Note that most commercial aircraft travel at height between Flight Levels FL 200 and FL 350.

of the deadliest eruptions in the history of mankind, but caused only 57 deaths. The loss of life would have been much greater if a warning had not been issued based on monitoring and scientific studies, and a zone of restricted access had not been established. This illustrates the importance of monitoring and research to reduce the direct impact of volcanic eruptions.

Mason *et al.* (2004) report that during the past 36 Ma, 42 VEI 8 eruptions have been identified. The authors indicate that these eruptions are not evenly distributed in time but seem to cluster in two pulses over the past 36 Ma. Periods with as many as 22 events/Ma and down to 1.4 event/Ma have been identified. More recent examples are the eruptions of Taupo (around 24,000 BC; Wilson, 2001), Toba (around 74,000 BC; Rose & Chesner, 1987; Williams, 2012; Svensson *et al.*, 2013), and Yellowstone (around 640,000 BC; Christiansen, 2001), for which the impacts have been studied in detail.

More recent large eruptions with a VEI of 5, 6 or 7 include Thera (≈1630 BC), Vesuvius (79 AD), Laki (1783), Tambora (1815), Krakatau (1883), Novarupta (1912) and Pinatubo (1991). Each of these eruptions (except Novarupta, due to the remoteness of the area) generated immediate loss of life and structures at local distances (through the generation of pyroclastic flows, ash and gas emissions, tsunamis) as well as long-term losses at regional and global distances. These eruptions impacted the climate for long periods by injecting ash in the stratosphere at high altitudes (Tambora's ash column height reached 43 km) and triggering temperature changes which heavily impacted the harvest and led to famine and epidemics in several areas of the planet: the year 1816, following Tambora's eruption, is recalled as 'the year without summer', and generated abnormal temperatures in China, Europe and North America.

When focusing on the potential impact of volcanic eruptions on modern society, it is straightforward to go back a few years and recall the eruption of the Icelandic volcano Eyjafjallajökull. This minor VEI 3 to 4 eruption generated an ash plume with a height of approximately 9 km, which created the highest level of air travel disruption in Europe since the Second World War for about one week. The large economic loss (estimated between US$2 and $5 billion; Daniell, 2011) derived from the closure of most European airspace. However, grounding air travel prevented civil aviation disasters, thus saving thousands of human lives. Should a new Novarupta VEI 6 eruption occur in the Aleutian Range in the future, what would be the consequences for civil aviation?

In several instances over recent decades, civil aviation has come very close to disasters caused by volcanic eruptions, resulting from ash turning into a glass coating inside the aircraft's engines, blocking their normal functioning. The most striking examples are British Airways Flight BA 9 (24 June 1982) and KLM Flight 867 (15 December 1989). BA 9 flew at an altitude of 11,300 m into a cloud of volcanic ash generated by the eruption of Mount Galunggung, Indonesia. All four engines failed, causing, for the next 16 minutes, a descent of the aircraft without power to a height of 3,650 m, when the pilot managed to restart three engines and make a successful emergency landing in Jakarta, Indonesia. KLM 867 flew through a thick cloud of volcanic ash from Mount Redoubt while descending into Anchorage International Airport. All four engines failed. After a fall of more than 5,000 m the pilot managed to restart the engines and safely land (Casadevall, 1994).

As a consequence of these episodes the International Civil Aviation Organization (ICAO) established the Volcanic Ash Warning Study Group in 1982. In 1991 Volcanic Ash Advisory Centers (VAACs) were set up to liaise between meteorologists, volcanologists and the aviation industry and issue early warnings to pilots flying over airspace subject to risks of volcanic eruption.

The many active volcanoes in Indonesia, Japan, Kamchatka Peninsula, Alaska, Aleutian Islands, South America, Papua New Guinea, Hawaii, Iceland and South Europe make it clear that at a large scale, communications and exchange of goods is constantly subject to the big threat of a large volcanic eruption. An obvious question arises: if a VEI 3–4 eruption in Northern Europe blocked air traffic in Europe for a week, inconveniencing thousands of travellers and inhibiting the exchange of any type of goods, what would be the consequences of a larger eruption, of, say, VEI 7, similar to that which occurred at Tambora only 200 years ago? What consequences would result from a Plinian eruption of Vesuvius similar to the one that occurred in 79 AD, or an eruption at Phlegraean Fields, an area with the potential of generating VEI 7 eruptions located in the heart of the Mediterranean area?

Immediate and long-term casualties, long-term disruption to air traffic with consequent interruption of provisions of numerous primary goods, including medications and tools to support health care, short- and long-term climatic changes impacting agriculture and local hydrogeological systems, potential loss of energy, water and soil contamination, and the risk of epidemics would be some of the direct consequences of a large eruption striking highly populated areas.

Table 6. Overview of major volcanic eruptions with regional to global impacts and/or major fatalities. MCD: Main cause of death. VEI: Volcanic Explosivity Index.

Year	Location	VEI	km³	Deaths	Comment
2011	Puyehue-Cordon Caulle, Chile	4	0.3		
2010	Merapi, Indonesia	4		353	MCD: pyroclastic flows
2010	Eyjafjallajökull, Iceland	4	0.25	0	Caused severe air traffic disruption
1991	Pinatubo	6	6–16	847	MCD: failing roofs
1985	Nevado de la Ruiz, Colombia	3	0.03	25,000	MCD: Lahar
1980	St Helens	5	1	57	
1919	Kelut, Indonesia			5,100	MCD: mudflows
1912	Novarupta, Alaska	6	15–30	unknown	
1902	Mount Pelee, Martinique	4	>0.1	29,000	MCD: pyroclastic flow
1902	Santa Maria, Guatemala	6	20	>5,000	
1883	Krakatau, Indonesia	6	21	36,000	MCD: tsunami
1882	Galunggung, Indonesia	5		4,000	MCD: mudflows
1815	Tambora, Indonesia	7	150	92,000	MCD: starvation
1783-85	Laki and Grimsvoth, Iceland	6	14	9,400	MCD: famine and fluorine poisoning; deaths are for Iceland only
1660	Long Island	6	30		
1650	Kolombo	6	60		
1631	Vesuvius, Italy			3,500	MCD: mud and lava flows
1600	Huaynaputina	6	30		
1580	Billy Mitchell	6	14		
1477	Baroarbunga, Iceland	6	10		
1280	Quilotoa	6	21		
969±20	Changbai, China	7	76–116		
230	Taupo	7	120		
79	Vesuvius, Italy	5	2.8–3.8	3,400	MCD: ash flows
1610±14 BC	Santorini	7	99		
4350 BP	Kikai	7	80–220		
5550±100 BC	Kurile	7	140–150		
5677±50 BC	Crater Lake	7	150		
26500 BC	Oruanui, New Zealand	8			
73000±4000 BP	Toba, Indonesia	8	2500–3000		Killed up to 60% of the global population; MCD: starvation
640000 BP	Yellowstone	8	1000		

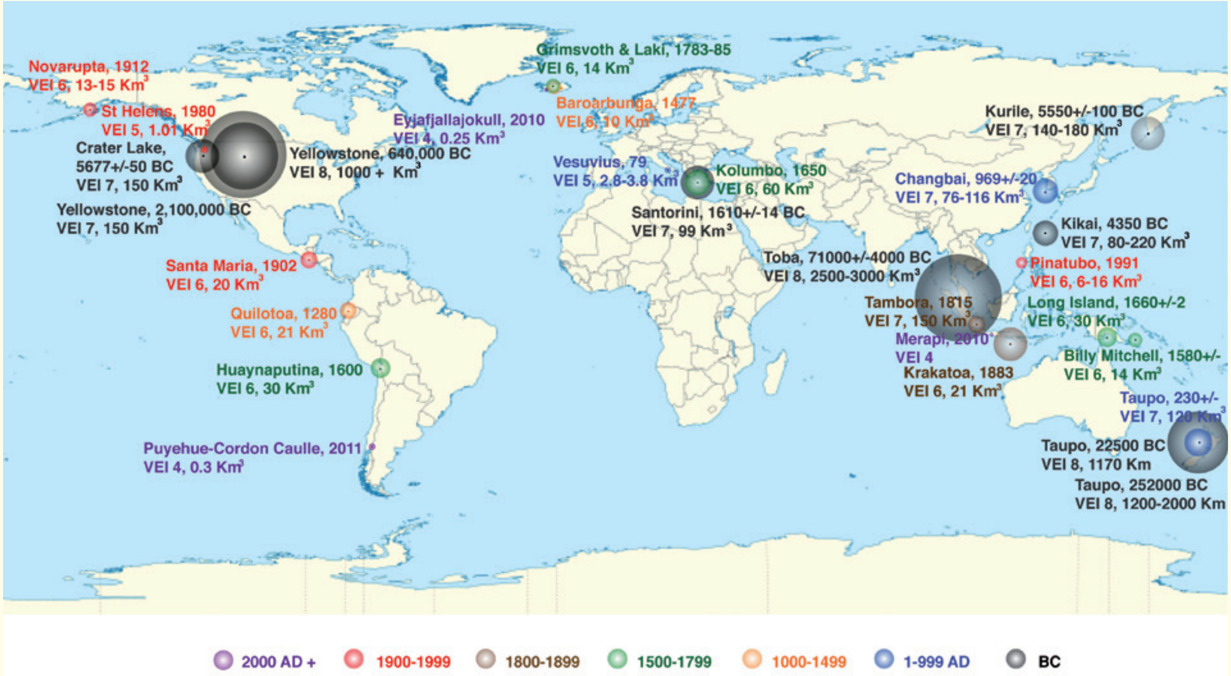


Figure 12. Major volcanic eruptions during the last 2,000 years and selected eruptions during the last 2 Ma.

Large eruptions can also impact climate, anthropogenic infrastructure and resource supplies on a global scale. Some of the larger eruptions during recent centuries provide examples that may allow us to assess what impacts the recurrence of similar events under today's conditions might have. However, six of the seven largest volcanic eruptions known in the Holocene took place while the global population was far below 1 billion (Figure 13).

The eruption of Laki in Iceland in 1783 caused about 9,350 deaths in Iceland. Although there was little direct impact, the eight-month emission of sulfuric aerosols resulted in a large distribution of the ash cloud (Figure 14) causing one of the most important climatic and socially repercussive events of the last millennium. The consequences for Iceland – known as the Mist Hardships – were catastrophic. An estimated 20–25% of the population died in the famine and from fluorine poisoning after the fissure eruptions ceased. Around 80% of sheep, 50% of cattle, and 50% of horses died because of dental and skeletal fluorosis from the 8 million tons of hydrogen fluoride that were released. There is evidence that the Laki eruption weakened African and Indian monsoon circulations, reducing precipitation over areas in Africa. The resulting famine that afflicted Egypt in 1784 cost it roughly one-sixth of its population. The eruption also affected the southern Arabian Peninsula and India. In Great Britain, the summer of 1783 was known as the 'sand-summer' because of the ash fallout. An estimated 25,000 people died in the UK because of breathing problems. Impacts

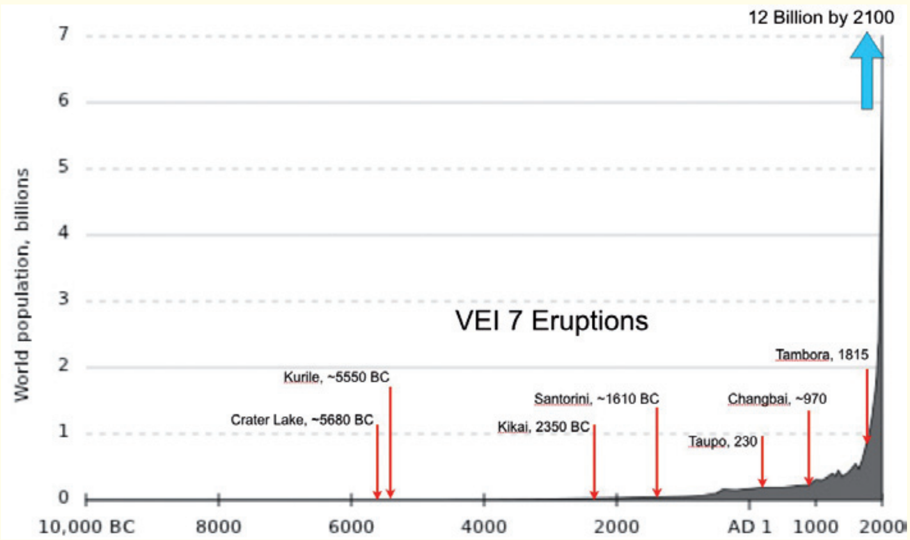


Figure 13. VEI 7 eruptions during the Holocene, and global population. Recent studies indicate that we are heading for a global population of 12 billion by 2100. For details on the eruptions, see Table 6.

Table 7. Historic volcanic eruptions had large environmental impacts and most of them would today have far-reaching impacts disrupting crucial infrastructure at a continental to global scale.

Deaths	Volcano	Year	Cause of death	VEI
92,000	Tambora, Indonesia [1]	1815	Starvation	7
36,000	Krakatau, Indonesia [1]	1883	Tsunami	6
29,000	Mt. Pelee, Martinique	1902	Ash flows	4
25,000	Ruiz, Colombia	1985	Mudflows	3
14,300	Unzen, Japan	1792	Tsunami	?
9,350	Laki, Iceland [1-2]	1783	Starvation	6
5,110	Kelut, Indonesia	1919	Mudflows	?
4,011	Galunggung, Indonesia	1882	Mudflows	5
3,500	Vesuvius, Italy	1631	Mud and lava flows	?
3,400	Vesuvius, Italy	79	Ash flows	5

1. These eruptions are presented in more detail as examples. 2. Only deaths in Iceland are counted.

Figure 14. Extent of areas impacted by volcanic ash during the Laki, Iceland eruption in 1783.

Figure 15. Extent of area impacted by volcanic ash during the Mount Tambora eruption in 1815.

were reported throughout Europe, North America, and the Gulf of Mexico. The eruptions contributed to several years of extreme weather in Europe.

The eruption of Mount Tambora in 1815 is the volcanic event with the largest number of direct fatalities, 71,000, in historic times. The ash cloud (Figure 15) caused global climate anomalies that including the 'volcanic winter', and 1816 became known as the 'year without a summer'. Crops failed and livestock died in much of the Northern Hemisphere, resulting in the worst famine of the 19th century. The resulting 'stratospheric sulfate aerosol veil' caused persistent dry fog in the northern United States. Average global temperatures decreased by about 0.4–0.7 K causing significant agricultural problems around the globe. Climate impacts are illustrated by frost and snow in June and subsequent months along the east coast of the USA. Part of Europe experienced a cooler summer and a stormier winter. This pattern of climate anomaly has been blamed for the severity of the typhus epidemic in southeast Europe and the eastern Mediterranean between 1816 and 1819, as well as the worldwide spread of a new strain of cholera originating in Bengal in 1816.

The eruption of Krakatau, Indonesia, in 1883 caused 36,500 deaths. After several months of increasing activity, the August 27, 1884 eruption was the most intense and could be heard 3,110 km away in Perth, Western Australia and in the island of Rodrigues near Mauritius 4,800 km away. The ash cloud covered a large fraction of South-East Asia and reached western Australia (Figure 16). The energy released is estimated at 200 megatons of TNT. Ash was injected into the atmosphere to an estimated height of 80 km. Each of the August 27, 1884 explosions was followed by a tsunami, with one estimated at over 30 m in height. A large area of the Sunda Strait and a number of places on the Sumatran coast were affected by pyroclastic flows, which generated the tsunamis when they collapsed in the ocean.

Figure 16. Extent of direct impact of the Krakatau, Indonesia eruption, 1883.

These examples illustrate that for volcanic eruptions of VEI 7 or 8, the risk of dramatic reductions in food supply at the local, regional and global level is very high. Large volcanic eruptions leave a significant number of fingerprints on the environment, as they impact the biosphere at different levels and can generate dramatic short or long-term climate changes (Self, 2006; Self & Blake, 2008). One example was the VEI 8 Toba eruption in Sumatra about 74,000 years ago, which released roughly 800 km^3 of ash and aerosols into the atmosphere, which covered much of Southeast Asia to a depth of more than 10 cm (Matthews *et al.*, 2012; Petraglia *et al.*, 2012), enough to destroy much of the vegetation, and cooling mid-latitude temperatures by 5–15 K for several years (Jones, 2007). Smil (2008) notes that today "a Toba-sized eruption in a similar location would, besides killing tens of millions of people throughout Southeast Asia, destroy at least one or two seasons of crops needed to feed some 2 billion people in one of the world's most densely populated regions. This alone would be a catastrophe unprecedented in history, and it could be compounded by much reduced harvests around the world. Compared to these food-related impacts, the damage to machinery, or the necessity to suspend commercial flights until the concentrations of ash in the upper troposphere returned to tolerable levels, would be a minor consideration."

Perhaps even more threatening than the immediate destruction of crops is the possibility that global crop yields would be significantly reduced for several years by sharply reduced temperatures. At present, there are no good estimates of the crop losses we might expect from such a multi-year global temperature drop, but we can get some hint from the emerging literature estimating the effects of global warming on agriculture. The 2007 IPCC Assessment Reports suggests that even a fall of a few Kelvin would have a substantially negative effect on crop yields, and that losses increase sharply for larger changes (Parry *et al.*, 2007).

The most important volcanic gas in terms of the potential climate impacts of eruptions is sulfur dioxide (SO_2), but few studies have focused on the amount and temporal distribution of SO_2 emission during major eruptions (Mandeville *et al.*, 2009). A study of the degassing of the magmas during the eruption of Mt. Mazama about 7,700 years B.P., which created Crater Lake, Oregon, indicated that the amount of mantle sulfur degassed may be larger than previously thought. The amount of SO_2 for the Mt. Mazama eruption is estimated to be an order of magnitude more than for the 1991 VEI 6 Pinatubo eruption (Mandeville *et al.*, 2009). The climate impact of volcanic eruptions is complex. For the Pinatubo eruption, which injected about 17 megatons of SO_2 into the middle and lower stratosphere, model studies indicate that the climate impact was associated with stratospheric warming and a global tropospheric cooling (Stenchikov *et al.*, 1998), which on the northern hemisphere separates into a tropospheric summer cooling and winter warming pattern (Kirchner *et al.*, 1999). The Pinatubo eruption caused an average global cooling of 0.5 K over three years (Ward, 2009). It can be expected that a VEI 7 eruption could have a much larger climate impact, which under present-day conditions could be devastating for food security.

3.7 Comparison of Geohazards and Other Natural Hazards

For modern society, geohazards are among the most impactful natural hazards at recurrence intervals of up to several decades. Over the last few decades, earthquakes combined with tsunamis, as well as floods and droughts, have caused the main fraction of loss of life and damage. As a consequence, DRR is focused on these events, and successes in DRR are mainly related to these hazards.

Other hazards that have the potential to challenge civilisation at the core include solar storms, viruses, and climate change impacts (Figure 17). Anthropogenic climate change is rapidly increasing the impacts of extreme temperatures, and it could well be that a change along the lines indicated in

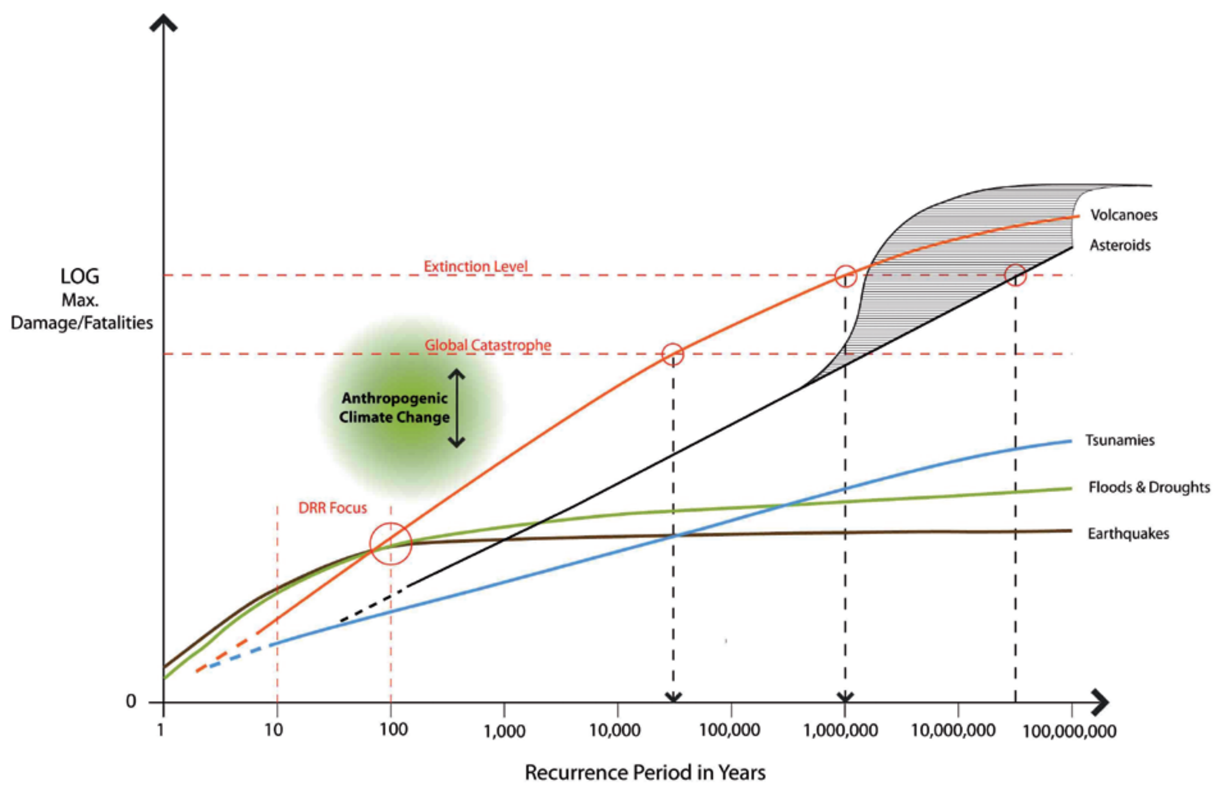


Figure 17. Qualitative comparison of the disaster risk associated with natural hazards. Not included are solar storms and extreme temperature events. Note that DRR focuses mainly on events experienced in the recent past, i.e. events with recurrence periods of 10 to 100 years.

the Intergovernmental Panel on Climate Change (IPCC) assessments could soon turn extreme temperature events into major hazards with the potential of global disasters. Likewise, a change in flood and drought magnitude and frequency could lead to higher impacts of the hazards with the potential of global catastrophe due to indirect effects on food and water security. The combined impacts of anthropogenic climate change thus could be the most important hazard on timescales of a few decades up to centuries. The uncertainty in full impact ranges from major disasters to global catastrophes.

Pandemics have the potential to cause global catastrophes in terms of the loss of life. The so-called Black Death, peaking in Europe in the years 1346–53, was one of the most devastating pandemics in human history, causing an estimated 75 to 200 million deaths (e.g. Hays, 2003). The 'Spanish Flu' pandemic, which lasted from 1918 to 1920, killed between 3 and 5% of the global population at that time. The memory of these global events has led to a global awareness of the risk, and any sign of a potential pandemic leads to an international response. The 2014 outbreak of Ebola in West Africa is the most recent case, which triggered a global response.

The extremely high dependency of modern society on communication, internet, and power has created a vulnerability to solar storms that did not exist when the last powerful solar storm hit the earth in 1927 (Kappenman, 2012). Under today's conditions and interdependencies, a comparable storm could have devastating long-lasting global consequences. In particular, high-voltage transformers in the power grid are most likely to fail in a geomagnetic storm, and they are also among the parts of the grid most difficult to replace (Kappenman, 2012).

The risk associated with less-frequent, high-impact events has been assessed in several recent studies (e.g. Smil, 2008; Schweickart *et al.*, 2008). A main conclusion was that "because NEO [near-Earth object] impacts represent a global, long-term threat to the collective welfare of humanity, an international program and set of preparatory measures for action should be established" (Schweickart *et al.*, 2008). Recently the International Asteroid Warning Network (IAWN) was established (see http://minorplanetcenter.net/IAWN for details) as part of the United Nations' effort to mitigate the near-Earth object (NEO) impact threat. Mitigation includes detection, follow-up, and characterisation of NEO impact threats as well as the development of possible deflection techniques. Acknowledging that international response capacity is needed to deal with any early warning of a large NEO approaching Earth, the Space Missions Planning Advisory Group (SMPAG) was created in 2013 with the primary purpose “to prepare for an international response to a NEO threat through the exchange of information, development of options for collaborative research and mission opportunities, and to conduct NEO threat mitigation planning activities.”

It is worthwhile to note that for large bolides that could cause X-events, recurrence periods exceed 1 Ma. For recurrence periods of up to 1 Ma, large volcanic eruptions (magnitude 8 or more) are associated with larger risks than these impactors (Mason *et al.*, 2004). Consequently, the global community should take the threat of a major volcanic eruption as seriously as that of a major impact. A major volcanic eruption could easily kill (through the many indirect effects, in particular, food scarcity) a higher percentage of the global population than the Spanish Flu, if it occurred without any global preparation efforts. Therefore, there is an urgent need to develop global mechanisms to detect a looming eruption as early as possible and to have an internationally coordinated response to an early warning.

4. Disaster Risk, Resilience, Antifragility and Adaptive Capacity

With the global population exceeding seven billion and the prospect of it reaching 12 billion by 2100 (Gerland *et al.*, 2014), humanity faces the crucial challenge of developing in a very limited time an effective programme to reduce the risk of global disasters and catastrophes caused by natural hazards and, in particular, by extreme geohazards. Following Glavovic (2013), it is suggested that metrics should be developed to measure progress towards four aspects of sustainable communities: (1) disaster risk and vulnerability; (2) resilience and antifragility; (3) adaptive capability; (4) livelihood.

Disaster risk results from the vulnerability of those communities exposed to natural hazards. The study of the vulnerability of human and natural systems to hazards is a relatively new interdisciplinary field, which is developing particularly with a view on climate effects and other natural hazards. A common language has not been developed yet, and experts from different fields assign different meanings to the terms used (e.g. Dolan & Walker, 2003). In particular, approaches differ between the natural and social sciences (e.g. Brooks, 2003).

A general assumption is that decisions on risk management need to take into account the probability of a hazard occurring, and the ability of a human socio-economic system or an ecosystem to cope with the hazard. The ability of a community to cope with hazards and to recover from the resulting disturbances is addressed within the concept of resilience. The ability to learn from a disaster and not just return to pre-event conditions is at the core of antifragility (Taleb, 2012).

Following the approach common to natural sciences, we distinguish between hazards and their probability, sensitivity of the built environment and community vulnerability to these hazards, and the exposure of the assets to potential hazards. The product of these three factors determines the risk (Box 1). The separation of these factors is important to understand how past evidence can be used to assess the disaster risk associated with future occurrences of extreme geohazards.

As pointed out earlier, for extreme hazards this approach may underestimate the risks because the available statistics are insufficient to estimate reliable probabilities for the extremes. Another complication results from the fact that the time dependence of the three factors in the equation is very different. For most geohazards, the recurrence as determined by their PDF does not change much over time during time intervals relevant to human societies. Thus the past provides information on recurrence, except for the extreme end of the hazard spectrum (as pointed out in Section 3). However, the past tells us little about the disaster risk associated with these hazards because sensitivities, vulnerabilities and exposure have changed dramatically over time. In particular, the last few decades have seen rapid development of urban areas and crucial infrastructure in hazardous areas, including megacities. An extreme example is Tokyo, which increased in size from roughly 1 million in 1900 to more than 30 million in 2000. While exposure has increased, in many areas sensitivity and vulnerability have changed due to a transition of the built environment to high-tech infrastructure, with low resilience with respect to failures, and a metabolism of interdependent processes and communities. In particular, the increasing interdependencies between services such as power, communication, transportation, water, sewage, food, health, and so on, in an increasingly interconnected world, as well as the lack of redundancies, increases vulnerability on all spatial and temporal scales.

Box 1

Risk equation for a given hazard h with recurrence time interval T, and intensity I, the associated risk $r(I)$ expressed in currency is given by

$$r_h^T(I, x, t) = p_h^T(I, t) \cdot S_h^{a(x,t)}(I, t) \cdot v(a, x, t) \quad (2)$$

where x is the location, t time, p the probability density function (PDF) of the hazard giving the probability that the hazard with intensity I will occur in the considered recurrence interval, S the sensitivity of the asset a exposed at location x to hazard h at intensity I, and v being the value of a. To assess the total risk R associated with a hazard, we can use

$$R_h^T(x, t) = \int_0^{I_{max}} r_h^T(I, x, t)\, di \quad (3)$$

(modified from Plag & Jules-Plag, 2013). Equations (2) and (3) provide a basis for risk assessment and prioritising of mitigation, adaptation and monitoring. The risk is strongly dependent on the chosen recurrence time interval. Selecting a short time interval may seriously underestimate the risk, while a very long interval may lead to unrealistically high risks. Assets can be any system from a single building, a transportation infrastructure, a city, or a socio-economic system, to an ecosystem or a natural resource such as groundwater. Here, 'sensitivity' is used to indicate the damage a hazard would cause to an asset if the asset were to be exposed to the hazard. In many publications, the sensitivity factor is denoted as 'vulnerability'. 'Sensitivity' is used rather than 'vulnerability' to avoid misunderstanding. Climate scientists tend to consider vulnerability in terms of the likelihood of impacts of weather- and climate-related events (Nicholls *et al.*, 1999) or the damage inflicted by changes in climate (outcome vulnerability) (e.g. Kelly & Adger, 2000; Pielke Sr. *et al.*, 2012), while social scientists often consider vulnerability as the set of socio-economic factors determining the ability of a social system to cope with stress or change (contextual vulnerability) (Allen, 2003; Glavovic, 2013). As defined here, sensitivity does not depend on the hazard actually occurring but is a latent characteristic of the asset. For example, one building may be more sensitive to fire hazards than another building, independent of the fire actually occurring. All three factors in Equation (2) depend on time. Both natural and anthropogenic assets at a given location can change and their value can change as well. Sensitivity of the assets also can change over time. In particular, adaptation can reduce sensitivity, while pre-stress can increase it. If we denote the impact of adaptation at time t on sensitivity by $\alpha(t)$, then sensitivity is given by

$$S_h^{a(x,t)}(I, t) = S_h^{a(x,t)}(I, t)\big|_{t=t_0} - \int_{t_0}^{t} \alpha(t)\, dt. \quad (4)$$

The probability p of a hazard h of intensity I occurring within time interval T also depends on time. Particularly for climate-related hazards, climate change will change p.

For most natural hazards, including most geohazards, there are limited options to impact p. However, in some cases, land use can significantly change the PDF of a hazard (e.g. for floods, droughts, landslides). Likewise, climate (in particular changes in precipitation and temperature) can modify the PDF significantly. An example is the increasing melting of permafrost in northern Canada and Alaska, which has led to increased landslides that threaten roads and pipelines. Increased precipitation and periods of more rapid snow melt can change the PDF for floods and droughts (e.g. Solomon *et al.*, 2007). Human action can change seismic hazards through large reservoirs, water extraction (e.g. Amos *et al.*, 2014) and, most recently, fracking.

The main measures for risk reduction lie in a reduction of sensitivity of assets to hazards and overall community vulnerability and, if possible, the spatial exposure of assets. Adaptation and mitigation are insurance against the risk. While the risk equation [see Equations (2) and (3)] provides a basis for a quantitative analysis of the risk, willingness to engage in adaptation and mitigation depends on risk perception. Zahran *et al.* (2008) found that those cities that had suffered more from extreme events were more willing to commit to a Cities for Climate Protection (CCP) campaign. The challenge of extreme geohazards is that they are infrequent and risk awareness is generally low, and costs for adaptation and mitigation are often postponed.

As mentioned above, another relevant term is resilience, the ability of a system to absorb disturbance while retaining its basic function and structure (Walker & Salt, 2006). A recent definition includes preparedness and the ability to adapt to change ('resilience' means the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions; The White House, 2013). Social and ecological resilience are related (Adger, 2000). For a social system, resilience is the ability to cope with external and internal stresses as a result of social, political and environmental change. For an ecological system, resilience is the ability of the ecosystem to maintain itself in the face of disturbance. Particularly for communities depending on ecological and environmental resources for their livelihoods, there is a clear link between social and ecological resilience. On a global scale, resilience of humanity is linked to the resilience of the global biosphere to human interference, including human climate forcing (National Research Council, 2005) coupled with natural climate variations which are often quite large (Rial *et al.*, 2004; Meko *et al.*, 2007). There are global boundaries whose transgression may put the global ecosystem into a new state, which could be acceptable for ecosystems, but outside of the safe operating space for humanity (Rockström *et al.*, 2009a,b). Decisions on mitigation of impacts on ecosystems has to account for this link between ecological and social resilience.

Adaptive capacity is important for events with long unfolding times, such as climate change and sea level rise. However, it is also important to adapt to changing knowledge about risks and new emerging threats. The growing understanding that extreme geohazards, in particular extreme volcanic eruptions, pose a grossly underrated risk requires significant adaptation of major parts of modern societies, if there is a consensus that the global disaster risk associated with these rare but high-impact events should be reduced.

Extreme geohazards have short unfolding times, leaving little room to increase preparedness when an event has started to unfold. General preparedness needs to be developed as part of the design of communities. For earthquakes, the unfolding time is extremely short, and early warnings that a particular event is going to happen are absent or unreliable. Therefore, immediate warnings during the initial phase of an event are crucial to mitigate impacts on infrastructure and to avoid cascading effects. Preparedness of both the built environment and the social fabric is the basis for this mitigation. For tsunamis, warning times can be as short as a few minutes, so preparedness of the population has to be the focus of DRR.

For extreme volcanic eruptions, precursors are very likely to occur over a longer period of weeks to years. Monitoring systems that can detect these precursors and models capable of quantifying and assessing the likelihood of an extreme event are ingredients for a significant reduction of the direct risk. The main challenge of these events is the indirect risk resulting from global interdependencies.

The livelihood of community depends on efficient DRR, but is crucial for any capacity to engage in DRR. Communities that are struggling to secure their livelihood are fragile and have less capacity to engage in DRR, develop resilience, or increase adaptive capabilities. Effective DRR has to take this into account.

DRR strategies depend on the scale of the hazard. A thorough risk assessment is the starting point for all scales and events. Tools for risk assessment at local scale are rapidly developing (e.g. Bernknopf *et al.*, 2006), but methodologies and tools for assessments of global risks are less developed and often ad hoc. Early warning systems need to be an integral part of DRR. The interaction of societal and environmental conditions impact vulnerability and risk, and monitoring of socio-ecological processes appears important for detection of changes in the risk spectrum.

For hazards with predominantly local scales, the optimal strategy is to avoid hazardous areas where possible. Risk can also be reduced through a built environment adapted to the hazards to which it is exposed, and redundancy can help to ensure service availability during and after hazardous events. Increasing modularity reduces interdependencies and helps to reduce the scale of disasters. The role of social capital in limiting the impact of hazardous events, particularly in the recovery phase, is increasingly recognised.

For hazardous events at regional scales, robustness of the built environment is crucial. Global redundancy and modularity are central to avoid cascading effects and far-reaching impacts. The need for redundancy and modularity conflicts to some extent with globalisation of the economy. Having reserves is equally important, and, again, this is in conflict with an economy operating to a large extent on a just-in-time principle.

For the hazards with potentially global extent, DRR is extremely challenging. Being equipped with 'lifeboats' should be the aim for global civilisation, just as a ship should have sufficient lifeboats for its passengers in the event of an emergency. A focus on food and water reserves, technology redundancy, and social community resilience are therefore prerequisites for any successful DRR.

For a better understanding of how human interactions with hazardous events can increase, or reduce, the impacts, information on the processes that unfold during and after events is needed.

Currently, a human observatory is lacking that collects data needed to understand these processes. Much of the data currently available are collected in the post-event phases. The use of Big Data and modern technology could help to increase the socio-economic and ecological database.

It also needs to be emphasised that extreme hazards have the potential to reduce civilisation to pre-industrial or pre-civilisation levels and lead to the 'collapse of everything' (Casti, 2012). Despite the low probability of such events, their risk is increasing due to the increasing complexity of modern society. To reduce risk, there is an urgent need to be precautionary with respect to the extreme hazards and to be prepared for possible 1 in 1,000 or 10,000-year events, that could happen in the next 100 years. The immediate benefit would be that we would also be better prepared to handle more frequent events that cause an increasing number of fatalities and rapidly escalating damage.

5.
Cost-Benefit Analysis of Planning for Extreme Geohazards

To estimate the risk associated with extreme volcanic eruptions, first the potential damage of a volcanic event on the scale of the eruption from what is now Lake Toba (in Indonesia) is considered (see Section 3). This eruption, which occurred about 75,000 years ago, released 2500–3000 km^3 of debris into the atmosphere, and the resulting climatic changes are thought to be responsible for the death of 60% of the human population living at that time (Rose & Chesner, 1987). Using extreme value theory, Mason et al. (2004) estimate the lower bound for the frequency of such M8 or larger eruptions to be 1.4 to 22 events/Ma (see Section 3.6). This results in a probability of between 2.2×10^{-5} (about 1 in 45,000 years) and 1.4×10^{-6} (about one in 714,000 years) that a M8 or larger eruption occurs in any given year.

What would be the consequences of a M8 eruption today? Smil (2008) noted that a repeat of Toba in the near future would devastate food supply: (1) directly, by depositing a metre or so of ash over an area of several million square kilometres, thus destroying one or two seasons of crops needed to feed two billion people; and (2) indirectly, by cooling the global climate by 5–15 K for a period of up to a decade, and severely reducing crop yields. An eruption on such a scale would also cause substantial physical destruction (damage to buildings, etc.), but such destruction would – unless the eruption occurred very near a densely populated area – likely pale in comparison to the loss of life which would follow from the reduced food supply.

It is impossible to guess with precision what the loss of life would be if the Toba eruption were repeated in the modern world, but it is likely that it would be the greatest catastrophe since the dawn of civilisation. One hopes that the worldwide death rate would be much less than the 60% seen in the aftermath of Toba's eruption 75,000 years ago, but it would be unrealistic to expect fewer fatalities than in some of the 20th century's tragedies, such as the 1918 flu pandemic, which killed between 3% and 5% of the world's population (Taubenberger & Morens, 2006). For the sake of round numbers, it is assumed here that the worldwide fatality rate would be about 10% if the eruption occurred as a surprise (the conclusion that the benefits of allocating resources to reduce mortality greatly exceed the costs will turn out not to be overly sensitive to this number).

To proceed with the cost–benefit analysis (CBA), a decision needs to be made how much it is worth spending to reduce the mortality risks. The traditional approach has been to put a monetary value on each life which we can expect to save by some policy change. The value of one life saved is called the value of a statistical life (VSL). VSLs are typically calculated either from labour market data (e.g. looking at how much of a wage premium workers demand for performing more dangerous jobs), from product market data (e.g. by looking at how much extra consumers will pay for a safer car, or a house in a less polluted area), or by survey (e.g. by asking people directly how much they would pay to avoid a particular probability of death). Basically, the idea is to see how much of their own money people will spend to reduce their own mortality risks – the idea is that government policies should not force taxpayers to 'purchase' more or less safety through government policies than they are willing to purchase when they choose freely (see Viscusi & Aldy, 2003, for a survey on VSL calculations). The US Department of Transportation has recently determined that the appropriate VSL for potential road fatalities in the US is $9.1 million (Trottenberg & Rivkin, 2013).

This means that the DOT assumes that a US citizen is (or should be) willing to pay about $910 to eliminate a 1 in 10,000 risk of a fatality.

To have a VSL for the whole world, it needs to be taken into account that wealthier people are willing to pay more for safety, and that US citizens are much wealthier than the world average. The DOT review referred to above suggests that the VSL rises one-for-one with income, so a country with an income which is one quarter of the US level should have a VSL which is one quarter as much. It turns out that the average US citizen's income is just over four times larger than the world average income (World Bank, 2013), suggesting a world VSL of $2.22 million.

Now the cost of a Toba-scale eruption from the fatalities alone without considering costs due to damage and impacts on the global economy can be calculated. If the fatality rate is 10% and the probability that the event occurs in any given year is between 1.4×10^{-6} and 2.2×10^{-5}, then the probability of a random person dying in any particular year is between 1.4×10^{-7} and 2.2×10^{-6} . With a VSL of $2.22 million, the average person should be willing to pay between $0.16 and $1.00 per year to eliminate this risk. Given a global population of just over 7 billion, this corresponds to $1.1–7.0 billion per year.

There are three main reasons why this estimate might be too low. Firstly, it considers only Toba-scale eruptions; there are many smaller eruptions which could also occur and be very damaging. Including these in the calculation would at least double the expected damage. Secondly, assuming that the VSL rises one-for-one with income probably understates the worldwide average VSL. The one-for-one estimate is actually at the high end of the range. Viscusi & Aldy (2003) suggest that the VSL rises (or falls) at about only half this rate with income changes. If the Viscusi & Aldi estimates are used, then the worldwide average VSL would be closer to $4 million, and the willingness to pay would roughly double. Thirdly, this ignores all costs apart from loss of life, including losses to the capital stock (which are likely to be small relative to the cost of lives lost), and the much larger costs associated with potential large-scale conflict and partial breakdown of civilised life, which might be associated with a geohazard at this scale. Incorporating these additional costs could raise the expected damage by an order of magnitude or more. Incorporating these sources might raise willingness to pay by a factor of 40.

It is not possible to completely avoid the hazard posed by volcanic eruptions. Asteroids can, in principle, with enough warning and the right technology, be diverted to cause no damage, but large volcanoes cannot be stopped. Nevertheless, it would be possible to mitigate much of the loss of life, given sufficient warning. The losses discussed above have their origins in the disruption of the food supply. Given warning, these losses can be mitigated by organisation, storage and knowledge. Organisation of the food supply would become much more important as food became more scarce: currently a large proportion of the food that we grow goes to waste. Given time, systems of food transport and processing could be re-designed to generate less waste (though at higher cost). Storage is another strategy: even with only a year of warning, large-scale storage could mitigate the risks. For example, much of the corn currently used to produce ethanol or to feed cattle could be set aside. Finally, knowledge: if the world cools by 5–15 K for a period of several years, then to preserve the food supply, crops would not be planted in the same places that they are planted now. Broadly speaking, crops would have to 'move south', but knowing exactly what to plant where is not obvious. With one or two years' notice, it would be possible to run large-scale agricultural experiments to determine optimal crop plantings for a temporarily cooler climate.

Such strategies could avoid many of the deaths which would otherwise follow from such an abrupt change in climate. It might even be possible to avoid all unnecessary starvation. To be conservative, and for the sake of round numbers, it is assumed that the expected death toll could be reduced by half. Given that eliminating the risk of death from a Toba-repeat would be worth at least $1.1 to $7.0 billion per year, eliminating half of the risk would be worth at least somewhere between $0.5 and $3.5 billion per year. That is the value of knowing in advance if another Toba is coming.

How much would it cost to find out if another Toba-like eruption is coming? The amount is not known exactly, but it is a lot less than $3.5 billion per year. For reference, the 2014 budget for the US Geological Survey provides $24.7 million for volcano hazards (US Geological Survey, 2013). Given that the US represents about 1/15 of the land surface of the Earth, then bringing the rest of the world up to US levels of monitoring would only cost about 15 x $24.7 million, or about $370 million per year. This is less than the lower boundary of the expected benefit from greater monitoring.

For the far more frequent VEI 7 events, the eruption of Mount Tambora in 1815 provides an example. There have been at least seven VEI 7 eruptions in the last 10,000 years, and we assume the probability of a VEI 7 event occurring in any given year to be on the order of 7 x 10^{-4}. Although these events would have a lesser impact than a VEI 8 event, being two to three orders of magnitude more likely than a VEI 8 event, the associated risk (i.e. hazard probability times sensitivity times value of assets) is comparable, underlining the need to invest in risk reduction by developing a reliable monitoring system.

To sum up, conservative estimates of the benefits of increased monitoring are between $0.5 and $3.5 billion per year. The actual benefits may be 10 to 100 times larger taking into account the whole distribution of volcano sizes and the non-food-supply-related avoidable costs of an eruption. Conservative estimates of the costs of a global monitoring system are at $370 million per year; this is possibly a substantial overestimate, since it assumes that there are no economies of scale in monitoring volcanoes. Nevertheless, the benefits of a global monitoring system are at least 10 times larger than the costs. If the actual monitoring costs are two or three times lower, and if the expected benefits are 10 or 100 times larger, then the total benefits may be hundreds or thousands of times greater than the total costs.

6.
Confronting Disaster Risks for Extreme Geohazards

Risks associated with extreme geohazards challenge humanity on a global scale. These risks range from extinction level events to global disasters, which could kill a few percent of the global population (Hempsell, 2004b). The complexity of modern society increases these risks and has the potential to multiply the threat. A particular focus of DRR needs to be on intermediate level events that can cause global catastrophes resulting in the loss of at least a quarter the global population (Hempsell, 2004a).

Key questions that need to be answered to develop programmes that can help confront global risks resulting from extreme geohazards include:

- What is the status of readiness of countries to face the occurrence of a large or extreme geohazard?
- What kind of infrastructures are currently available to efficiently cope with the emergencies generated by large or extreme geohazards?
- What could help reduce the effects of a large or extreme geohazard?

The development of an effective DRR programme and of a consequent robust resilience programme needs to be based on a holistic approach, addressing scientific, technical, logistic, social, policy and governance issues related to these hazards and involving all the principal stakeholders facing this challenge, including natural and social scientists and policy makers.

A governance process is needed to bring together all relevant stakeholders for a community process (Section 6.1). To better understand the vulnerabilities and assess the risk, focused research is needed (see Section 6.2). A main tool supporting such an holistic approach would be a global network of monitoring systems, based on synergetic technologies capable of acquiring and sharing in real-time (or near real-time) high quality data recorded on a global scale (Section 6.3). The systematic and comprehensive analysis of such data would allow the development of a deeper understanding of the phenomena associated with geohazards and programmes of Disaster Risk Reduction and Resilience (D3R) to issue early warnings.

6.1 Governance for Extreme Geohazards

Adaptive management works best for slow changes, such as a slow change in climate, sea level rise, and so forth. It has limited applicability for extreme events with short unfolding times. For these events, evidence-based, proactive management is required.

Major geohazards occur at least every few years somewhere in the world, but may only strike a particular country once or twice a century, or perhaps not at all. Such geohazards are the main focus of international risk reduction programmes. These hazards present an important opportunity to learn from their impacts on an increasingly complex society. This is the main reasoning behind the principle of antifragility proposed by Taleb (2012).

There is, however, a need for a societal consensus on how to address disaster risk associated with extreme hazards. Any such consensus will depend significantly on the available economic resources and the threats from anthropogenic hazards. In some parts of the developing world, economic resources are insufficient to address major risks, and in others, anthropogenic hazards are overwhelming.

Preventing disasters from recurring involves the balancing of costs and benefits of policies aimed at

DRR (Stein & Stein, 2014). A crucial aspect of this balance is that the risks and benefits have to be estimated, accounting for significant uncertainties to infer the probabilities of the future events.

Paradoxically, innovation during recent decades, in particular urban innovation, has increased the disaster risk and coupled this risk to the sustainability crisis. Only more innovation can reduce disaster risk and lead us out of the sustainability crisis. Governance needs to ensure that innovations lead to more resilience and reduced disaster risk instead of increasing the risks. Participatory, deliberative governance for DRR requires representation from all societal groups. The four-order scheme proposed by Glavovic (2013) can be used to define disaster risk outcomes and associated societal processes. This framework can be implemented in the context of deliberative democracy and governance with participation of the community.

The current dialogue between science and society is not fully capable of supporting deliberative governance and a democratising of knowledge. Most scientific knowledge is created independently of those who could put it to use, so a transition to co-design and co-development of knowledge involving a broad stakeholder base (Mauser *et al.*, 2013) is necessary to address the disaster risk associated with extreme events. This transition may cause more responsibility and even liability for science. A central question relates to the responsibility and liability of science participation in deliberative evidence-based governance. Could the scientist still be the expert who creates 'peer-reviewed' knowledge with a rather vague responsibility and no liability for it being correct or being put to use? Or would the scientist have to assume a role with higher liability for what is provided as a contribution to the deliberations? The controversy in the aftermath of the 2009 L'Aquila earthquake and the discussions around the IPCC illustrate the difficulties associated with the current scientific knowledge system in the context of a crisis, which can only be mastered based on evidence and directional innovation. Likewise, these difficulties also exist in DRR, where consequential decisions have to be made that can impact economy, life, and the livelihood of many.

Risk awareness and monitoring is highly uneven across the world, creating two kinds of problem. Firstly, potential hazards are much more closely monitored in wealthy countries than in the developing world. But the largest hazards are global in nature, and it is critical to get as much forewarning as possible to develop an effective response. The disasters and near-misses of the recent past show that using scientific knowledge, particularly during the early warning phase, can reduce disasters. This suggests that a well-developed global monitoring system for geohazards is needed in support of the early detection of extreme hazards (see Section 6.3). Secondly, low risk awareness combined with poverty, corruption, and a lack of building codes and informed land use management contributes to conditions that turn hazards into disasters throughout much of the developing world. Democratising knowledge about extreme geohazards is very important to inform deliberations of disaster risks and community strategies that can reduce the disaster risk by increasing resilience and adaptive capacities without compromising the livelihood of communities.

DRR should focus not only on the hazardous event alone, but also on the processes that create the disaster and can be modified. The understanding of how to reduce the complexity that facilitates processes leading to disasters is still in its infancy. Much attention in disaster risk reduction has focused on increasing the robustness of infrastructure. Any built environment is only robust to a certain threshold. Recent events that have exceeded these thresholds have brought to the forefront the importance of the social fabric and social networking in resilience. Resilience strongly depends on social capital, defined as collective benefits derived from strong community norms of cooperation and mutual assistance. A focus on building social capital can create resilience and must be a key element of DRR. Occurrence of hazards that cause, or nearly cause, disasters present a unique opportunity to learn more about the processes triggered by the hazard. This 'antifragile' approach (Taleb, 2012) requires the collection of sufficient data prior, during and after the hazard. Therefore, a socio-ecological observation system needs to be designed and implemented that provides the basis to enable lessons to be learned from disasters.

At present, DRR-related efforts are fragmented. Current assessment of global risk resulting from geohazards is still relegated to the scientific literature (e.g. Smil, 2008). Traditional DRR programmes focus on more frequent hazards and more at local to regional scales. The IPCC is restricted to the risks from climate change and its impacts. The World Economic Forum assesses global risks, but does not cover geohazards in these global risks in terms of likelihood or impacts (Figure 18 and World Economic Forum, 2014).

Figure 18. Evolving Global Risk Landscape 2007–2014 according to the World Economic Forum. Upper diagram: in terms of likelihood; lower diagram: in terms of impacts. From World Economic Forum (2014).

6.2 **Knowledge Assessments and Research Needs**

A comprehensive review of the current understanding of high-impact geohazards and the challenges posed to DRR and the disaster risk management cycle was undertaken during the European Science Foundation (ESF)–European Cooperation in Science and Technology (COST) high level research conference held in 2011 in Spain (see http://www.geohazcop.org/workshops). The participants of this conference recognised the work done by the international geohazards community to improve the knowledge of geohazards and the threat to society. Major research efforts have improved our understanding of the causes and processes of geohazards and have advanced our knowledge of the hazardous areas.

Continental topography is at the interface of deep Earth, surface and atmospheric processes (Cloetingh *et al.*, 2007; Cloetingh & Willet, 2013a). Topography influences society, not only as a result of slow landscape changes but also in terms of how it impacts on geohazards and the environment (Figure 19). When sea-, lake- or ground-water levels rise, or land subsides, the risk of flooding increases, directly affecting the sustainability of local ecosystems and human habitats. On the other hand, declining water levels and uplifting land may lead to higher risks of erosion and desertification. In the recent past, catastrophic landslides and rock falls have caused heavy damage and numerous fatalities in Europe. Rapid population growth in river basins, coastal lowlands and mountainous regions, together with global warming, associated with increasingly frequent exceptional weather events, are likely to

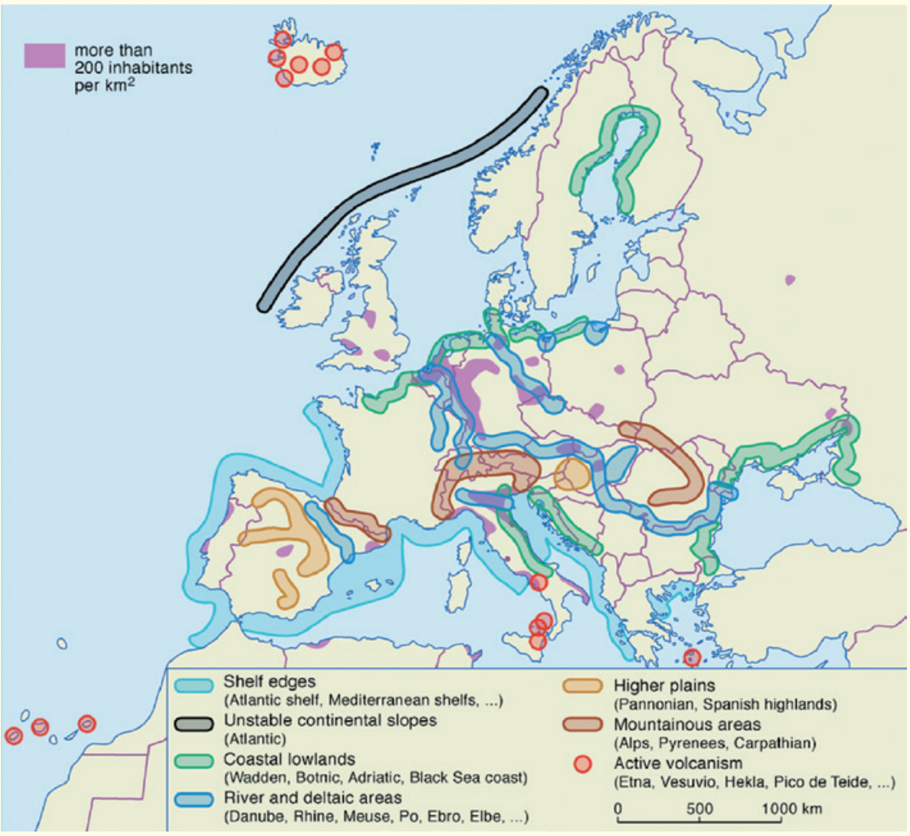


Figure 19. Areas of vulnerability due to vertical movements in Europe, demonstrating the link between demography and environmental tectonics in Western and Central Europe (after Cloetingh *et al.*, 2007).

exacerbate the risk of flooding and devastating rock failures. Along active deformation zones, earthquakes and volcanic eruptions cause short-term and localised topography changes. These changes may present additional hazards, but at the same time permit the quantification of stress and strain accumulation, a key control for seismic and volcanic hazard assessment (Cloetingh & Willet, 2013b). Although natural processes and human activities cause geohazards and environmental changes, the relative contribution of the respective components is still poorly understood (Cloetingh & Haq, 2015). That topography influences climate has been known since the beginning of civilisation, but it is only recently that we have been able to model its effects in regions where good (paleo-) topographic and climatologic data are available.

The present state and behaviour of the shallow Earth system is a consequence of processes operating on a wide range of time scales. These include the long-term effects of tectonic uplift, subsidence and the development of river systems, residual effects of the ice ages on crustal movement, natural climate and environmental changes over the last millennia and up to the present, and the powerful anthropogenic impacts of the last century. If we are to understand the present state of the Earth system, to predict its future and to engineer our use of it, this spectrum of processes, operating concurrently but on different time scales, needs to be better understood. The challenge taken up by the TOPO-EUROPE programme, initiated by ESF, is to describe the state of the system, to monitor its changes, to forecast its evolution and, in collaboration with others, to evaluate modes of its sustainable use by human society (Holm *et al.*, 2013). The recent implementation of the European Plate Observing System (EPOS) is a milestone in this endeavour.

Many measures required to prepare for, and adapt to, hazards have been developed. Likewise, international programmes informing governments, decision makers, and the general public on disaster risks, and ways to reduce these risks, are being conducted. The current process towards a follow-on for the Hyogo Framework is an example of how the international community is addressing the disaster risk. The ESF 2011 conference on extreme geohazards acknowledged the work of the Geohazards Theme of Integrated Global Observing Strategy Partnership (IGOS-P) (see the 2007 Frascati Declaration of the Third International Workshop on Geohazards and Marsh and the Geohazards Theme Team, 2004) and the Geohazards Community of Practice (GHCP) of the Group on Earth Observations (GEO) (in particular, Geohazards Community of Practice, 2010). At the same time, the conference concluded in the conference declaration (Geohazards Community of Practice, 2012) that the challenge of extreme geohazards is linked with a number of urgent research needs. Besides a better understanding of the nature of the extreme hazards, including their PDFs, the vulnerabilities of modern society need to be better understood. Mitigation and adaptation science are only beginning to address global risks (Moss *et al.*, 2013).

The Global Earthquake Model (GEM) "aims to combine the main features of state-of-the-art science, global collaboration and buy-in, transparency and openness in an initiative to calculate and communicate earthquake risk worldwide. One of the first steps towards this objective has been the open-source development and release of software for seismic hazard and risk assessment called the OpenQuake engine" (Silva *et al.*, 2014). Research needs to focus on a similar global model for extreme volcanic eruptions.

As mentioned above, understanding processes that are triggered by extreme geohazards and can lead to global disasters is part of the quest to reveal underlying hidden risks. Community disaster resilience taking into account the possibility of cascading effects and chains of failure is at the beginning of its development as a scientific field. Simulation of selected extreme hazards under present conditions can help to assess the disaster risk.

For example, the impacts of the ash fallout of large eruptions on marine bio-production are not known. Under today's strained fishery, a reduction of bio-productivity would increase the global food price with severe consequences for social stability.

A socio-ecological observing system will be needed to identify the essential variables to be observed. Likewise, a human observatory is required to provide observations about human interactions with the built and natural environment prior, during and after hazardous events. Here, too, the essential variables have not been defined yet.

The US National Research Council (2013) considered the threat of abrupt climate change impacts and proposed an early warning system on time scales of several years to decades. These warnings are comparable to a timely warning for a looming major volcanic eruption. What is poorly known is how the global community would react if a warning on the emerging threat of such an event were to be published, so research into the reaction to warnings on emerging global risks is necessary.

6.3 Monitoring and Early Warning

Modern societies are progressively clustering around megacities, often located in hazardous areas and hosting complex infrastructures. Most of the megacities include structures which are not designed to resist the impact of geohazards. These include historical buildings, or buildings in areas with high poverty built with no adherence to building codes, if those exist. This implies that even for more frequent geohazards, the risk of large loss of life, property and community services has dramatically increased. Many buildings hosting crucial human and infrastructure elements are exposed to hazards, and this can lead to chains of failure. When exposing fragile communities to extreme geohazards, the effects caused by chains of failure are likely to have devastating consequences.

Because extreme geohazards are rare, it is natural to think that it is not worth designing cities or relief organisations to protect against them. However, the risk of global disasters or catastrophes triggered by these hazards is extremely high, particularly in the context of a complex, globally connected civilisation. Moreover, in the context of multi-hazard scenarios, even moderate geohazards can lead to extreme consequences. In combination with the transition of the planet from the Holocene into a new post-Holocene era, the risk of global disasters or catastrophes is extremely high, particularly given the complexity and global connectedness modern society. Considering the precarious nature of global society, the definition of major hazards becomes to some extent arbitrary (WMO, 2014). Therefore, efforts to reduce the risks associated with the extreme end of the hazard spectrum should be considered. Monitoring potential threats is of the utmost importance.

To be capable of addressing the risks associated with extreme geohazards implies a need to build robust resilience for a very large spectrum of hazardous events. In this context, a crucial step towards the development of effective disaster risk reduction and of a significant level of resilience is based on comprehensive monitoring of all the phenomena and parameters which might help issue early warnings in every part of the planet.

The ability to issue early warnings is tightly related to the availability of reliable networks recording very high quality data, having high operational standards and very low downtime: all the available global, regional and local networks with such high quality performance criteria should be used to monitor every area of the planet and transmit data to operational centres in near real-time in order to assure rapid analysis and identification of a risk increase.

At present, there is no system for monitoring geohazards comparable to those in place for monitoring extraterrestrial threats. NASA has a congressional mandate to catalogue all near-Earth objects greater than one kilometre in size, as the impact of such an object would be catastrophic. Efforts are also under way to demonstrate technologies that would help to reduce the threat of an impact of an approaching asteroid (see i). An example is the cooperation be-tween ESA and NASA on the precursor asteroid hazard mitigation mission Asteroid Impact and Deflection Assessment (AIDA). AIDA is made up of two independent components, the US-led asteroid kinetic impactor Double Asteroid Redirect Test (DART) and the ESA-led Asteroid Impact Mission (AIM). AIM is a small mission of opportunity that has the goal to characterise the Dydimos binary asteroid system and at the same time to demonstrate technologies enabling future small and medium missions. The main goal of the AIDA cooperation is to prove the ability to modify the dynamics of Didymos in a way that is measurable both by the AIM observation spacecraft and from Earth-based facilities.

There is no equivalent organisation with a mandate to monitor potentially catastrophic geohazards. Hempsell (2004a) finds that "there are several possible space systems that could either prevent, or control or provide escape safe havens, but all require a significant improvement of the space infrastructure in terms of size and improved economics to make them viable." Hempsell concludes that addressing the threat of global catastrophes should be the prime focus of space infrastructure policy. Satellite monitoring systems can provide crucial information on many phenomena occurring on the Earth's surface, or in the atmosphere (e.g. Hempsell, 2004b). However, such monitoring might, in some cases, need to be complemented with additional monitoring systems: integrating this information with other types of data acquired with different monitoring networks can provide a more comprehensive view on the status of a certain region of the Earth and assess the level of risk in that area. For example, space-based observations complemented with ground-based tracking stations provide a basis for the global monitoring of Earth surface deformations (Plag & Pearlman, 2009).

Monitoring is important because the risks posed by extreme geohazards are so large – both in terms of the immediate fallout and of multi-year climate change – that they ideally would be known years in advance of the actual event. A warning period of several years would be enough to increase food reserves and perform the agricultural research necessary to maintain adequate crop yields in a sharply colder climate and potentially modified water cycle. Recent research has made attempts to improve forecasting of major eruptions (Druitt *et al.*, 2012; Sheldrake, 2014; Bebbington, 2014), but with the limited amount of currently available data, reliable and robust forecasts are still not possible and further development is needed.

Two key questions to ask are: (1) How many monitoring networks are available today to acquire information on a global scale on specific key parameters associated with a given type of geohazard? (2) Given a specific geohazard, what is the current level of integration of the information acquired through different monitoring networks to assess the potential increase of risk?

During the past few decades, several international organisations have developed monitoring networks to collect data at a local, regional or global scale. For example, the Global Seismographic Network (GSN) of the Incorporated Research Institutions for Seismology (IRIS) acquires and shares data recorded by seismic stations distributed around the world. The National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA) operates two tsunami warning centres. The Alaska Tsunami Warning Center (ATWC) in Palmer, Alaska, serves the areas of Alaska, British Columbia, Washington, Oregon, and California; the Pacific Tsunami Warning Center (PTWC) in Ewa Beach, Hawaii, has the double function of monitoring the area of Hawaii and acting as the national and international warning centre for tsunamis in the Pacific area. Following the Great Sumatra earthquake in 2004, a tsunami monitoring service has been developed for the Indian Ocean region.

For volcano monitoring, traditional observation systems, based on seismic waves, ground deformation, geochemical analysis, satellite and infrared monitoring, have been used for decades. These monitoring techniques have supported studies of volcanic hazards mostly on local and regional scales, rather than on a global scale. Despite progress in the availability of techniques for highly accurate measurements of ground deformations, both through space-geodetic tracking stations based on the Global Navigation Satellite System (GNSS) and through Interferometric Synthetic Aperture Radar (InSAR) (e.g. Plag *et al.*, 2009), there is currently no service providing low-latency information on Earth surface deformation covering at least the areas of potential volcanic eruptions. In principle, such a service could be based on a low number of Synthetic Aperture Radar (SAR) satellites in combination with a global network of Continuous GNSS (CGNSS) stations. The achievable accuracy is better than 1 mm/year (Hammond *et al.*, 2011). Currently more than 11,000 CGNSS stations provide data to public data archives (see http://geodesy.unr.edu/billhammond/gpsnetmap/GPSNetMap.html). Combining selected stations with SAR measurements in a routine, low-latency analysis could provide a basis for a surface-displacement service as part of an early warning system. Moreover, such a service would have many other applications with immediate societal benefits.

In the last 15 years, the traditional systems for monitoring volcanoes have been complemented by infrasound, a re-emerging technology (after its quite extensive development during the 1950s). This technology detects acoustic waves propagating in the atmosphere with a frequency range below the audible threshold (Gossard & Hooke, 1975; Evers & Haak, 2009). Infrasound has great potential for volcano monitoring since volcanoes inject a large part of their energy into the atmosphere, generating infrasound waves. Infrasound monitoring provides a significant insight into the characteristics of volcanic eruptions, often going beyond the information retrievable through traditional monitoring technologies (Campus & Christie, 2009). Infrasound monitoring constitutes, therefore, an extremely valuable tool to help issue early warnings to both populations and the civil aviation authorities in the case of volcanic eruptions (Chen & Christie, 1995). Additional applications of infrasound technology include monitoring of avalanches, landslides, meteors (ReVelle, 2009; Edwards, 2009), severe storms (Garcés *et al.*, 2009; Hetzer *et al.*, 2009), auroras (Wilson *et al.*, 2009) and earthquakes (Mikumo & Watada, 2009), as well as specific atmospheric studies (Kulichkov, 2009; Le Pichon *et al.*, 2009; Blanc *et al.*, 2009; Drob *et al.*, 2009). These latter studies have the potential of generating significant progress in the modelling of the atmosphere and improving the accuracy of short- and medium-range weather forecasts.

Infrasound technology is today supported not only by a number of local networks but primarily by a global network. The International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban-Treaty Organization (CTBTO), comprising seismic, infrasound, hydroacoustic and radionuclide stations with a total of 337 facilities, has been designed to detect all nuclear explosions, but is capable of significantly contributing to the detection and monitoring of natural phenomena, including climate change (CTBTO Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, 2008) and, in particular, hazardous events (CTBTO Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, 2011). The global infrasound monitoring network of the IMS consists of 60 stations distributed worldwide. Most of these stations have been built and are currently fully operational, sending data to the CTBTO International Data Centre (Vienna, Austria) in compliance with extremely strict requirements for data quality, data availability and data transmission from the station to the International Data Centre. The contribution of the IMS Infrasound component of the CTBT Network to volcano monitoring has been proven to be essential in the last decade. The CTBTO provides its Member States, as well as the international and national institutions responsible for aviation safety, with all the relevant information to enabling early warnings to be issued.

Volcanoes, earthquakes and tsunamis are regularly recorded by IMS seismic and hydroacoustic stations. Following the 2004 Great Sumatra earthquake and tsunami, the CTBTO provides information in near real-time to tsunami warning centres, in particular those covering the Pacific and Indian Oceans, to help them issue more timely and precise warnings. At present, tsunami warning centres in 11 countries with a high tsunami risk receive data from around 110 CTBTO stations.

The recent report of the UNISDR 'Progress and Challenges in Disaster Risk Reduction' provides under Priority area 2, Core indicator 2.3 area a general overview of the existing early warning systems distributed worldwide and analyses the major challenges associated with these systems. The report also highlights the fact that most early warning systems are in place for floods, cyclones, earthquakes, tsunamis and droughts (UNISDR, 2014). This implies that there is an urgent need for consolidating a global monitoring network for volcanoes capable of issuing early warnings not only in areas locally affected by volcanic eruptions, but also in areas which could suffer on a regional and global scale from the consequences of major or extreme volcanic eruptions. The CTBTO IMS infrasound network can play a crucial role in this context.

In conclusion, the CTBTO IMS network is capable of providing a crucial contribution to monitoring natural hazards and issuing early warnings thanks to the simultaneous acquisition of high-quality data from stations based on four different technologies, distributed worldwide and transmitting data in near real-time to a single reference point, the International Data Centre. This unique characteristic puts the CTBTO in a key position to facilitate progress in DRR and to contribute to resilient communities and sustainable development.

CTBTO might also play a key role in facilitating the full integration of all the existing local, regional and global monitoring networks based on the four IMS monitoring technologies. This role also might be instrumental in generating a close synergy with the European Commission (which recently published the Joint Research Centre's Report 'Science for Disaster Risk Reduction', European Commission, Joint Research Centre, 2014), with UNISDR and with the GEO, thus facilitating the achievement of common targets in DRR and the establishment of the Global Earth Observation System of Systems (GEOSS). In this synergetic scenario the future delivery of sufficiently advanced early warnings might become more streamlined, thus helping to save life and property even in the case of extreme geohazards.

An example of an important recent development in this context is the decision by the European Strategy Forum for Large Scale Scientific Infrastructure (ESFRI) to include the European Plate Observing System (EPOS) in its implementation plan (see http://www.epos-eu.org) for the coming five years. EPOS is integrating the diverse but advanced European research infrastructures for solid Earth science, with a total value of 500 million euro. EPOS will build on new e-science opportunities to monitor and understand the dynamic and complex solid Earth system. EPOS will identify existing gaps and promote implementation plans with environmental, marine and space science to help solve the grand challenges facing the Earth and its people.

Integration of existing national and transnational research infrastructures will increase access and use of the multidisciplinary data recorded by the solid Earth monitoring networks, acquired in laboratory experiments and/or produced by computational simulations. Establishment of EPOS will foster worldwide interoperability in the Earth sciences and services among a broad community of users.

The social impact of the activities promoted and coordinated in EPOS in terms of disaster prevention and mitigation is evident. Indeed, open access to the multidisciplinary research infrastructure as well as the prompt and continuous availability of high quality data will not only stimulate innovative research on the Earth dynamics and processes that lead to catastrophic events, but will lead to new developments in disaster prevention research, and is therefore invaluable for improving hazard assessment and forecasting. The EPOS infrastructure will contribute to information, dissemination, education and training.

7. Conclusions and Recommendations

Geohazards cause large and increasing loss of life and property. The recent major geohazards that have caused disasters with global impacts are dwarfed by the largest geohazards that occurred during the Holocene. The potential impact on society of any such rare event tends to be ignored in the planning of land use, infrastructure, and socio-economic processes. While communities from the local to the global level learn increasingly to cope with the more frequent hazards, this does not imply that there is increasing resilience to low-probability high-impact events.

The recent extreme disasters have revealed gaps in the knowledge of geohazards available to policy- and decision-makers. Understanding the full spectrum of geohazards, including extreme events, is a prerequisite for disaster risk management and increased global resilience to these events. Reducing the disasters induced by the occurrence of extreme hazards at an acceptable economic cost requires a solid scientific understanding of the hazards. Although many scientific questions still need to be answered, the disasters are rarely the result of a lack of science. Rather, they often result from the lack of a process for understanding the available scientific knowledge and for using it in decision-making. Therefore, there is a need to move to a global science-based framework that would contribute to risk management for extreme hazards.

Human activities do not drive the occurrence of extreme geohazards, and humans have basically no – or very limited – means to prevent the occurrence of such events, especially volcanic eruptions. Choices need to be made on whether to prepare for extreme geohazards and how to respond to them (Stein and Stein, 2014). These choices include how much to invest in science and how to best leverage scientific investment. They also include how to mobilise all sectors at the scale that is commensurate with the scale of the extreme geohazards and their impacts. In particular, developing and engaging with a process for integrating science in decision-making is crucial.

Although in the last few decades earthquakes have been the main cause of fatalities and damage, the main global risk is large volcanic eruptions that are less frequent but far more impactful than the largest earthquakes. Due to their far-reaching effects on climate, food security, transportation, and supply chains, these events have the potential to trigger global disaster and catastrophe. The cost of response and the ability to respond to these events is beyond the financial and political capabilities of any individual country. An international geopolitical response will be required, where science has a unique and key role in preparation, response and mitigation.

Many cascading events are not likely to be predicted by science or to be included in the scientific discourse. To understand cascading hazards and cascading effects, it will be necessary to learn from past disasters (becoming antifragile; Taleb, 2012) and to explore the weaknesses of modern society through simulation of extreme events.

Why are we not prepared for extreme events? Reasons for this include the low perceived likelihood of such an event, low political sensitivity, and a disconnect between scientific communities and decision-makers; reasons for the lack of socially acceptable strategies include the cost of preparing for an extreme hazard, and, in some cases, the belief that consequences are so extreme that preparedness is futile. What is not among these reasons is a lack of scientific knowledge.

Risk awareness and monitoring is highly uneven across the world. As a result, potential hazards are much more closely monitored in wealthy countries than in the developing world. The global nature of extreme hazards requires as much forewarning as possible to develop an effective response. The disasters and near-misses of the past show that adherence to scientific knowledge, particularly during the early warning phase, can reduce disasters. This suggests that a strong global monitoring system for geohazards is needed, not least to support the early detection of extreme hazards.

Low risk-awareness combined with poverty, corruption, and a lack of building codes and informed land use management creates the conditions to turn hazards into disasters throughout much of the developing world. Democratising knowledge about extreme geohazards is very important in order to inform deliberations on disaster risks and community strategies that can reduce the disaster risk by increasing resilience and adaptive capacities without compromising the livelihood of communities.

A key element in DRR aimed at extreme geohazards is a volcano monitoring system. Such a system would not only be capable of providing timely warnings for looming extreme events but would also improve the observational database for urgently needed research on extreme hazards. Likewise, the system would improve the timely detection of more frequent geohazards, and it would provide a basis for improved early warnings.

For some eruptions, lead times are extremely short and DRR will require a reduction in sensitivity of infrastructure, an increase in community resilience, including risk awareness across the community, and adaptive capabilities to cope with potentially large long-term changes in environmental conditions. There are several core elements that are needed to address the global risk from extreme geohazards:

- It is recommended that a joint international and synergistic effort be made to establish a global scientific framework for strategic extreme geohazard science. This framework should be capable of delivering a tactical scientific response to hazards and extreme hazards. It should also seamlessly integrate and up-date science into warning, preparedness, mitigation and responses that are implemented by governments, communities, and the private sector on a global scale in order to minimise the detrimental global impacts of extreme geohazards. Such a framework could take into account lessons learned from NEO tracking in terms of monitoring and from the IPCC model in terms of knowledge assessment. As of today, no such scientific framework is available to assess the knowledge on global threats resulting from modern society being exposed to low-probability high-impact events.
- It is recommended that a better understanding be gained of the interrelation between topography, geohazards and the environment. The temporal evolution of topography needs to be assessed, not only during the recent past but also during the last 10 or so million years. There are however some complex problems inherent to paleo-topography analysis. Apart from dealing with topography that no longer exists, the dimensions and timing of events and the underlying dynamic processes that controlled topographic development, as well as the topographic life cycle, pose major challenges, the complexity of which cannot be solved by a single sub-discipline but requires support by other disciplines.
- It is recommended that scenario contingency planning be used to better understand the threats and reduce risk. For this, a few specific or generic extreme geohazards should be selected. A methodological and rational scientific analysis of event scenarios, including likely worst case scenarios, should be developed in cooperation with stakeholders and decision makers. A goal should be to work through the cascading hazards and outcomes identified by science and those recognised by stakeholders. The existing political opportunities and constraints, including the difficulties of implementation and the cost of not implementing, should be assessed. Options should be developed for how to manage the situation with the resources that will be available, rather than those that the scenario dictates should be available.
- It is recommended that risk awareness be increased in the population through dissemination of concise and clear information on the risk associated with hazards and through training for coping with emergency scenarios.
- It is recommended that a global monitoring system be put in place with the goal of providing early warning for emerging extreme volcanic eruptions. Two core elements of this monitoring system would be the operational monitoring of solid Earth surface displacements and of infrasound waves. Both monitoring components would have major societal benefits besides the early detection of emerging extreme eruptions.
- It is considered important to develop an informed global governance structure that could respond to emerging global threats and coordinate global measures to increase preparedness and resilience and reduce the risk of global disasters. In this con-

text, the recommended framework for strategic extreme geohazards science (and science for other extreme hazards) would inform the global governance system of any impending risk, and scenario contingency planning would provide guidance for disaster risk management.

As an immediate step to support research into early warning, it is also recommended that the Charter on Cooperation to Achieve the Coordinated Use of Space Facilities in the Event of Natural or Technological Disasters (see https://www.disasterscharter.org) be extended to cover cases where access to data could increase preparedness or where a looming extreme hazard might cause a disaster. The current charter only applies to cases where the disaster has already happened and has created a crisis. In the case of a disaster, the charter can be activated to give access to comprehensive data archives. For extreme geohazards, having access to data during the phase where the hazardous event is developing could lead to a better understanding of the potential for an extreme event and inform decisions to prepare for such an event.

Acknowledgements

This document is the result of many interactions of the authors with participants of the Geohazards Community of Practice (GHCP) of the Group on Earth Observations (GEO) at conferences and dedicated meetings. The authors would like to thank the community for its input and support. In particular, we would like to thank the reviewers of a near final draft for their valuable comments: Richard Lewis Bernknopf, Charles Connor, David Green, Charles Mandeville and Max Wyss.

Acronyms and Abbreviations

AIDA	Asteroid Impact and Deflection Assessment
AIM	Asteroid Impact Mission
ATWC	Alaska Tsunami Warning Center
CBA	Cost-benefit analysis
CCP	Cities for Climate Protection
CGNSS	Continuous GNSS
COST	European Cooperation in Science and Technology
CTBTO	Comprehensive Nuclear-Test-Ban-Treaty Organization
DART	Double Asteroid Redirect Test
DRR	Disaster Risk Reduction
D3R	Disaster Risk Reduction and Resilience
EPOS	European Plate Observing System
ESF	European Science Foundation
ESFRI	European Strategy Forum for Large Scale Scientific Infrastructure
GEM	Global Earthquake Model
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GHCP	Geohazards Community of Practice
GNSS	Global Navigation Satellite System
GSN	Global Seismographic Network
IAWN	International Asteroid Warning Network
ICAO	International Civil Aviation Organization
IDD	International Disaster Database
IGOS-P	Integrated Global Observing Strategy Partnership
IMS	International Monitoring System
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
IRIS	Incorporated Research Institutions for Seismology
NEO	Near-Earth Object
NOAA	National Oceanic and Atmospheric Administration
NWSv	National Weather Service
PDF	Probability Density Function
PTWC	Pacific Tsunami Warning Center
SAR	Synthetic Aperture Radar
SMPAG	Space Missions Planning Advisory Group
UNISDR	United Nations Office for Disaster Risk Reduction
VAAC	Volcanic Ash Advisory Centers
VEI	Volcanic Explosivity Index

References

Adger, W. N., 2000. Social and ecological resilience: are they related?, *Progress in Human Geography*, **24**(3), 347–364.

Allen, K., 2003. Vulnerability reduction and the community-based approach: A Philippines study, in *Natural Disasters and Development in a Globalising World*, edited by M. Pelling, pp. 170–184, Routledge, London.

Amos, C. B., Audet, P., Hammond, W. C., Burgmann, R., Johanson, I. A., & Blewitt, G., 2014. Uplift and seismicity driven by groundwater depletion in central California, *Nature*, **509**(7501), 483–486, doi: 10.1038/nature13275.

Avramenko, M. I., Glazyrin, I. V., Ionov, G. V., & Karpeev, A. V., 2014. Simulation of the airwave caused by the Chelyabinsk superbolide, *J. Geophys. Res. Atmospheres*, **119**(12), 7035–7050.

Bebbington, M. S., 2014. Long-term forecasting of volcanic explosivity, *Geophys. J. Int.*, **197**(3), 1500–1515.

Ben-Menahem, A., 1975. Source parameters of the Siberian explosion of June 30, 1908, from analysis and synthesis of seismic signals at four stations, *Physics of the Earth and Planetary Interiors*, **11**(1), 1–35, doi: 10.1016/0031–9201(75)90072–2.

Bernknopf, R. L., Rabinovici, S. J., Wood, N. J., & Dinitz, L. B., 2006. The influence of hazard models on GIS-based regional risk assessments and mitigation policies, *Int. J. Risk Assessment and Management*, **6**(4/5/6), 369–387.

Blanc, E., Le Pichon, A., Ceranna, L., Farges, T., Marty, J., & Herry, A., 2009. Global scale monitoring of acoustic and gravity waves for the study of the atmospheric dynamics, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

Bostrum, N., 2002. Existential risks – analyzing human extinction scenarios and related hazards, *J. Evolution and Technology*, **9**, Available at http://www.jetpress.org/volume9/risks.html.

Brooks, N., 2003. Vulnerability, risk and adaptation: A conceptual framework, Tech. rep., Tyndall Centre for Climate Change Research and Centre for Social and Economic Research on the Global Environment (CSERGE), School of Environmental Sciences, University of East Anglia, Norwich, U.K.

Campus, P. & Christie, D., 2009. The IMS Infrasound Network: Worldwide observations of infrasonic waves, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

Casadevall, T. J., 1994. The 1989–1990 eruption of redoubt volcano, Alaska: impacts on aircraft operations., *J. Volcanology Geothermal Research*, **62**(1), 301–316.

Casti, J. L., 2012. *X-Events – The Collapse of Everything*, HarperCollins Publisher, New York.

Chen, P. & Christie, D. R., 1995. Infrasonic detection of volcanic explosions by the CTBT international monitoring system: Implications for aviation safety, in *Proceedings 2nd Meeting International Civil Aviation Organization, Volcanic Ash Warning Study Group, Montreal, Canada, November 2*, CTBT.

Christiansen, R. L., 2001. The Quarternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana, Tech. rep., US Geol Surv Prof Pap 729, 1–146.

Cloetingh, S. and Haq, B. U., 2015. Inherited landscapes and sea level change. *Science*, **347** no. 6220, DOI: 10.1126/science.1258375Review.

Cloetingh, S. & Willet, S. D., 2013a. TOPO-EUROPE: Understanding of the coupling between the deep Earth and continental topography, *Tectonophysics*, **602**, 1–14.

Cloetingh, S. & Willet, S. D., 2013b. Linking deep earth and surface processes, *Eos, Trans. Am. Geophys. Union*, **94**(5), 53–54.

Cloetingh, S., Ziegler, P. A., Bogaard, P. J., Andriessen, P. A., Artemieva, I. M., Bada, G., van Balen, R. T., Beekman, F., Ben-Azvraham, Z., Brun, J.-P., Bunge, H. P., Burov, E. B., Carbonell, R., Facenna, C., Friedrich, A., Gallart, J., Green, A. G., Heidbach, O., Jones, A. G., Matenco, L., Mosar, J., Oncken, O., Pascal, C., Peters, G., Sliaupa, S., Soesoo, A., Spakman, W., Stephenson, R. A., Thybo, H., Torsvik, T., de Vincente G., Wenzel, F., Wortel, M. J., & TOPO-EUROPE working group, 2007. TOPO-EUROPE: The geoscience of coupled deep Earth-surface processes, *Global and Planetary Change*, **58**, 1–118.

CTBTO Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, 2008. The nuclear test-ban verification regime: an untapped source for climate change monitoring, Tech. rep., CTBTO, http://www.ctbto.org/fileadmin/user_upload/public_information/2008/01122008_climate_change_final_web.pdf.

CTBTO Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, 2011. Disaster warning and promoting human welfare – the civil and scientific uses of ctbto data, Tech. rep., CTBTO, http://www.ctbto.org/fileadmin/user_upload/public_information/2011/CSA_web.pdf.

Daniell, J. E., 2011. The CATDAT Damaging Earthquakes Database – 2010 – the year in review, Available at: http://earthquake-report.com/wp-content/uploads/2011/02/CATDAT-VOLC-Data-1st-AnnualReview-2010-James-Daniell-02.02.pdf

Dolan, A. H. & Walker, I. J., 2003. Understanding vulnerability of coastal communities to climate change related risks, *J. Coastal Research*, **SI 39**, Proceedings of the 8th International Coastal Symposium, Itajaí, Brazil, ISSN 0749-0208.

Drob, D. P., Meier, R. R., Michael Picone, J., & Garcés, M. M., 2009. Inversion of infrasound signals for passive atmospheric remote sensing, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

Druitt, T. H., Costa, F., Deloule, E., Dungan, M., & Scaillet, B., 2012. Decadal to monthly timescales of magma transfer and reservoir growth at a caldera volcano, *Nature*, **482**(7383), 7780.

Edwards, W. N., 2009. Meteor generated infrasound: Theory and observation, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

European Commission, Joint Research Centre, 2014. Science for disaster risk reduction, Tech. rep., European Commission, ISBN 978-92-79-27314-8.

Evers, L. G. & Haak, H. W., 2009. The characteristics of infrasound, its propagation and some early history, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

Fritz, H. M., Mohammed, F., & Yoo, J., 2009. Lituya bay landslide impact generated mega-tsunami 50th anniversary, *Pure and Applied Geophysics*, **166**(1-2), 153–175.

Garcés, M., Willis, M., & Le Pichon, A., 2009. Infrasonic observations of open ocean swells in the pacific: Deciphering the song of the sea, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

Geohazards Community of Practice, 2010. A Roadmap for the Geohazards Community of Practice of the Group on Earth Observations, Tech. rep., Geohazards Community of Practice of the Group on Earth Observations, available at http://www.geohazcop.org

Geohazards Community of Practice, 2012. Declaration on Extreme Geohazards and the Reduction of Disaster Risks, Tech. rep., Geohazards Community of Practice of the Group on Earth Observations, available at http://www.geohazcop.org/workshops/Sant_Feliu_2011/sant_feliu_declaration_i.php.

Gerland, P., Raftery, A. E., Ševčíková, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L., Fosdick, B. K., Chunn, J., Lalic, N., Bay, G., Buettner, T., Heilig, G. K., & Wilmoth, J., 2014. World population stabilization unlikely this century, *Science*, **346**(6206), 234–237.

Glavovic, B. C., 2013. Coastal innovation imperative, *Sustainability*, **5**(3), 934–954; doi:10.3390/su5030934.

Gorkavyi, N., Rault, D. F., Newman, P. A., Da Silva, A. M., & Dudorov, A. E., 2013. New stratospheric dust belt due to the Chelyabinsk bolide, *Geophys. Res. Lett.*, **40**(17), 4728–4733.

Gossard, E. & Hooke, W., 1975. *Waves in the Atmosphere: Atmospheric Infrasound and Gravity Waves-their Generation and Propagation*, Elsevier Scientific Publishing.

Gulick, S. P. S., Christeson, G. L., Barton, P. J., Grieve, R. A. F., Morgan, J. V., & Urrutia-Fucugauchi, J., 2013. Geophysical characterization of the Chicxulub impact crater, *Reviews of Geophysics*, **51**(1), 31–52.

Hammond, W. C., Blewitt, G., Li, Z., Plag, H.-P., & Kreemer, C., 2011. Contemporary uplift of the Sierra Nevada, western U.S. from GPS and InSAR measurements, *Geology*, **27**, doi: 10.1130/G32968.1.

Harbitz, C., Lvholt, F., & Bungum, H., 2014. Submarine landslide tsunamis: how extreme and how likely? *Natural Hazards*, **72**(3), 1341–1374.

Harkrider, D. G., 1964. Theoretical and observed acoustic-gravity waves from explosive sources in the atmosphere, *J. Geophys. Res.*, **69**(24), 5295–5321.

Hays, J. N., 2003. *The Burden of Disease – Epidemics and Human Response in Western Cultures*, Rutgers University Press.

Hempsell, C. M., 2004a. The potential for space intervention in global catastrophes, *J. British Interplanetary Society*, **57**, 14–21.

Hempsell, C. M., 2004b. The investigation of natural global catastrophes, *J. British Interplanetary Society*, **57**, 2–13.

Hetzer, C. H., Gilbert, K. E., Waxler, R., & Talmadge, C. L., 2009. Generation of microbaroms by deep-ocean hurricanes, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

Holm, P., Goodsite, M. E., Cloetingh, S., Agnoletti, M., Moldan, B., Lang, D. J., & Zondervan, R., 2013. Collaboration between the natural, social and human sciences in Global Change Research, *Environmental science and policy*, **28**, 25–35.

Jones, S. C., 2007. The Toba supervolcanic eruption: Tephra-fall deposits in India and paleoanthropological implications, in *The Evolution and History of Human Populations in South Asia*, edited by M. D. Petraglia & B. Allchin, p. 173-200, Springer.

Kappenman, J., 2012. A perfect storm of planetary proportions, *IEEE Spectrum*, pp. accessed on Nov. 4, 2014 at http://spectrum.ieee.org/energy/the-smarter-grid/a-perfect-storm-of-planetary-proportions.

Kelly, P. M. & Adger, W. N., 2000. Theory and practice in assessing vulnerability to climate change and facilitation adaptation, *Climatic Change*, **47**, 325–352.

Kirchner, I., Stenchikov, G., Graf, H.-F., Robock, A., & Antuna, J., 1999. Climate model simulation of winter warming and summer cooling following the 1991 Mount Pinatubo volcanic eruption, *J. Geophys. Res.*, **104**, 19039–19055.

Kulichkov, S., 2009. On the prospects for acoustic sounding of the fine structure of the middle atmosphere, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

Le Pichon, A., Vergoz, J., Cansi, Y., Ceranna, L., & Drob, D., 2009. Contribution of infrasound monitoring for atmospheric remote sensing, in *Infrasound Monitoring for Atmospheric Studies*, pp. 629–646, Springer.

Le Pichon, A., Ceranna, L., Pilger, C., Mialle, P., Brown, D., Herry, P., & Brachet, N., 2013. The 2013 Russian fireball largest ever detected by CTBTO infrasound sensors, *Geophys. Res. Lett.*, **40**(14), 3732–3737.

Mandeville, C. W., Webster, J. D., Tappen, C., Taylor, B. E., Timbal, A., Sasaki, A., Hauri, E., & Bacon, C. R., 2009. Stable isotope and petrologic evidence for open-system degassing during the climactic and pre-climactic eruptions of Mt. Mazama, Crater Lake, Oregon, *Geochimica et Cosmochimica Acta*, **73**, 29783012.

Marsh, S. & the Geohazards Theme Team, 2004. Geohazards Theme Report, Tech. rep., IGOS Integrated Global Observing Strategy.

Mason, B. G., Pyle, D. M., & Oppenheimer, C., 2004. The size and frequency of the largest explosive eruptions on Earth, *Bulletin of Volcanology*, **66**(8), 735–748; doi:10.1007/s00445–004–0355–9.

Matthews, N. E., Smith, V. C., Costa, A., Durant, A. J., Pyle, D. M., & Pearce, N. J. G., 2012. Ultra-distal tephra deposits from super-eruptions: Examples from Toba, Indonesia and Taupo Volcanic Zone, New Zealand, *Quaternary International*, **258**, 54–79.

Mauser, M., Klepper, G., Rice, M., Schmalzbauer, B. S., Hackmann, H., Leemans, R., & Moore, H., 2013. Transdisciplinary global change research: the co-creation of knowledge for sustainability, *Current Opinion in Environmental Sustainability*, **5**(34), 420-431.

Meko, D., Woodhouse, C. A., Baisan, C. A., Knight, T., Lukas, J. J., Hughes, M. K., & Salzer, M. W., 2007. Medieval drought in the upper Colorado River Basin, *Geophys. Res. Lett.*, **34**, L10705, doi:10.1029/2007GL029988.

Mikumo, T. & Watada, S., 2009. Acoustic-gravity waves from earthquake sources, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

Miller, D., 1960. Giant waves in Lituya Bay Alaska, USGS Prof Paper 354-C:51–83.

Moss, R. H., Meehl, G. A., Lemos, M. C., Smith, J. B., Arnold, J. R., Behar, D., Brasseur, G. P., Broomell, S. B., Busalacchi, A. J., Dessai, S., Ebi, K. L., Edmonds, J. A., Furlow, J., Goddard, L., Hartmann, H. C., Hurrell, J. W., Katzenberger, J. W., Liverman, D. M., Mote, P. W., Moser, S. C., Kumar, A., Pulwarty, R. S., Seyller, E. A., Turner II, B. L., Washington, W. M., & Wilbanks, T. J., 2013. Climate change – hell and high water: Practice-relevant adaptation science, *Science*, **342**, 696–698, DOI: 10.1126/science.1239569.

Muir-Wood, R., 2012. Annualized catastrophe mortalities and driving long term risk reduction, in *Proceedings of the 4th International Disaster and Risk Conference,* Davos, 26–30 August 2012.

National Research Council, 2005. *Radiative forcing of climate change: Expanding the concept and addressing uncertainties*, The National Academies Press, Washington, D.C., Committee on Radiative Forcing Effects on Climate Change, Climate Research Committee, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies.

National Research Council, 2013. *Abrupt Impacts of Climate Change: Anticipating Surprises*, National Research Council, Washington, D.C., Committee on Understanding and Monitoring Abrupt Climate Change and Its Impacts; Board on Atmospheric Sciences and Climate; Division on Earth and Life Studies.

Newhall, C. G. & Self, S., 1982. The volcanic explosivity index (VEI): An estimate of explosive magnitude for historical volcanism, *J. Geophys. Res.*, **87**, 1231-1238, doi:10.1029/JC087iC02p01231.

Nicholls, R. J., Hoozemans, F. M. J., & Marchand, M., 1999. Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses, *Global Environmental Change*, **9**, S69–S87.

Okal, E. A. & Synolakis, C. E., 2008. Far-field tsunami hazard from mega-thrust earthquakes in the Indian Ocean, *Geophys. J. Int.*, **172**(3), 995–1015.

Panizzo, A., De Girolamo, P., Di Risio, M., Maistri, A., & Petaccia, A., 2005. Great landslide events in Italian artificial reservoirs, *Natural Hazards and Earth System Science*, **5**(5), 733–740.

Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden P. J., & Hanson, C. E., eds., 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Petraglia, M. D., Ditchfield, P., Jones, S., Korisettar, R., & Pal, J. N., 2012. The Toba volcanic super-eruption, environmental change, and hominin occupation history in India over the last 140,000 years, *Quaternary International*, **258**, 119–134.

Pielke, R. A., Sr., R. Wilby, D. Niyogi, F. Hossain, K. Dairuku, J. Adegoke, G. Kallos, T. Seastedt, and K. Suding (2012), Dealing with complexity and extreme events using a bottom-up, resource-based vulnerability perspective, in *Extreme Events and Natural Hazards: The Complexity Perspective*, Geophys. Monogr. Ser., vol. 196, edited by A. S. Sharma *et al.* 345–359, AGU, Washington, D. C., doi:10.1029/2011GM001086.

Plag, H.-P. & Jules-Plag, S., 2013. Sea-level rise and coastal ecosystems, in *Vulnerability of Ecosystems to Climate*, edited by R. A. Pielke Sr., T. Seastedt, & K. Suding, vol. 4 of *Climate Vulnerability: Understanding and Addressing Threats to Essential Resources*, pp. 163–184, Elsevier.

Plag, H.-P. & Pearlman, M., eds., 2009. *Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020*, Springer Verlag, Berlin, Heidelberg.

Plag, H.-P., Altamimi, Z., Bettadpur, S., Beutler, G., Beyerle, G., Cazenave, A., Crossley, D., Donnellan, A., Forsberg, R., Gross, R., Hinderer, J., Komjathy, A., Mannucci, A. J., Ma, C., Noll, C., Nothnagel, A., Pavlis, E. C., Pearlman, M., Poli, P., Schreiber, U., Senior, K., Woodworth, P., & Zuffada, C., 2009. The goals, achievements, and tools of modern geodesy, in *Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020*, edited by H.-P. Plag & M. Pearlman, pp. 15–88, Springer Verlag, Berlin.

Pyle, D. M., 1995. Mass and energy budget of explosive volcanic eruptions, *Geophys. Res. Lett.*, **5**, 563–566.

Pyle, D. M., 2000. Size of volcanic eruptions, in *Encyclopedia of volcanoes*, edited by Sigurdsson, H. *et al.*, pp. 263–269, Academic Press.

ReVelle, D. O., 2009. Acoustic-gravity waves from impulsive sources in the atmosphere, in *Infrasound Monitoring for Atmospheric Studies*, Springer.

Rial, J., Pielke Sr., R., Beniston, M., Claussen, M., Canadell, J., Cox, P., Held, H., de Noblet-Ducoudre, N., Prinn, R., Reynolds, J., & Salas, J., 2004. Nonlinearities, feedbacks and critical thresholds within the Earth's climate system, *Climatic Change*, **65**, 11–38.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., & Foley, J., 2009. A safe operating space for humanity, *Nature*, **461**, 472–475.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S. I., Lambin, E., Lenton, T. M., Scheffer, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., & Foley, J., 2009. Planetary boundaries: exploring the safe operating space for humanity, *Ecology and Society*, **14**(2), 32, [online] URL: http://www.ecologyandsociety.org/vol14/iss2/art32/.

Rose, W. I. & Chesner, C. A., 1987. Dispersal of ash in the great Toba eruption, 75 ka., *Geology*, **15**, 913–917.

Schweickart, R. L., Jones, T. D., von der Dunk, F., & Camacho-Lara, S., 2008. Asteroid threats: A call for global response, Tech. rep., Association of Space Explorers Near-Earth Object Committee.

Self, S., 2006. The effects and consequences of very large explosive volcanic eruptions, *Phil. Trans. Royal Soc. A: Mathematical, Physical and Engineering Sciences*, **364**(1845), 2073–2083.

Self, S. & Blake, S., 2008. Consequences of explosive supereruptions, *Elements*, **4**(1), 41–46.

Sheldrake, T., 2014. Long-term forecasting of eruption hazards: A hierarchical approach to merge analogous eruptive histories, *J. Volcanology and Geothermal Res.*, **286**, 15–23.

Silva, V., Crowley, H., Pagani, M., Monelli, D., & Pinho, R., 2014. Development of the openquake engine, the global earthquake models open-source software for seismic risk assessment, *Natural Hazards*, **72**(3), 1409–1427.

Smil, V., 2008. *Global catastrophes and trends: The next 50 years*, MIT Press.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., & Miller, H. L., eds., 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stein, J. & Stein, S., 2014. Gray swans: comparison of natural and financial hazard assessment and mitigation, *Natural Hazards*, **72**(3), 1279–1297.

Stein, S., Stein, J., 2014. Playing against Nature: Integrating Science and Economics to Mitigate Natural Hazards in an Uncertain World (Wiley Works. John Wiley and Sons, Oxford).

Stenchikov, G. L., Kirchner, I., Robock, A., Graf, H.-F., Antuna, J. C., Grainger, R. G., Lambert, A., & Thomason, L., 1998. Radiative forcing from the 1991 Mount Pinatubo volcanic eruption, *J. Geophys. Res.*, **103**(D12), 13,837–13,857.

Svensson, A., Bigler, M. B., Blunier, T., Clausen, H. B., Dahl-Jensen, D., Fischer, H., Fujita, S., Goto-Azuma, K., Johnsen, S. J., Kawamura, K., Kipfstuhl, S., Kohno, M., Parrenin, F., Popp, T., Rasmussen, S. O., Schwander, J., Seierstad, I., Severi, M., Steffensen, J. P., Udisti, R., Uemura, R., Vallelonga, P., Vinther, B. M., Wegner, A., Wilhelms, F., & Winstrup, M., 2013. Direct linking of Greenland and Antarctic ice cores at the Toba eruption (74 ka BP), *Climate of the Past*, **9**(2), 749–766.

Taleb, N. N., 2012. *Antifragile – Things that gain from disorder*, Random House, Inc., New York.

Taubenberger, J. K. & Morens, D. M., 2006. 1918 influenza: the mother of all pandemics, *Rev. Biomed.*, **17**, 69–79.

Trottenberg, P. & Rivkin, R. S., 2013. Guidance on treatment of the economic value of a statistical life in U.S. Department of Transportation analyses, Revised departmental guidance, U.S. Department of Transportation.

UNISDR, 2014. Progress and challenges in disaster risk reduction – a contribution towards the development of policy indicators for the post-2015 framework for disaster risk reduction, Tech. rep., UNISDR, Vienna.

United Nations, Department of Economic and Social Affairs, Population Division, 2014. World Urbanization Prospects: The 2014 Revision, Highlights, Tech. rep. (ST/ESA/SER.A/352).

U.S. Geological Survey, 2013. Bureau highlights, Bh 53, USGS.

Vannucchi, P., Morgan, J. P., Della Lunga, D., Andronicos, C. L., & Morgan, W. J., 2015. Direct evidence of ancient shock metamorphism at the site of the 1908 Tunguska event, *Earth and Planetary Science Letters*, **409**, 168–174.

Vervaeck, A. & Daniell, J., 2012. CATDAT Damaging Earthquakes Database 2011 – annual review. Available at http://earthquake-report.com/2012/01/09/catdat-damaging-earthquakes-database-2011-annual-review/ accessed on September 21, 2013.

Viscusi, W. K. & Aldy, J. E., 2003. The value of a statistical life: a critical review of market estimates throughout the world, *J. Risk and Uncertainty*, **27**(1), 5–76.

Walker, B. & Salt, D., 2006. *Resilience Thinking – Sustaining Ecosystems and People in a Changing World*, Island Press, Washington, D.C., USA.

Ward, P. L., 2009. Sulfur dioxide initiates global climate change in four ways, *Thin Solid Films*, **517**, 3188–3203.

White House, 2013. Executive Order – Preparing the United States for the Impacts of Climate Change, Accessed at https://www.whitehouse.gov/the-press-office/2013/11/01/executive-order-preparing-united-states-impacts-climate-change on December 9, 2014.
Williams, M., 2012. Did the 73 ka Toba super-eruption have an enduring effect? insights from genetics, prehistoric archaeology, pollen analysis, stable isotope geochemistry, geomorphology, ice cores, and climate models, *Quaternary International*, **269**, 87–93.
Wilson, C. J. N., 2001. The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview, *J. Volcanol. Geotherm. Res.*, **112**, 133–174.
Wilson, C. R., Szuberla, C. A. L., & Olson, J. V., 2009. High-latitude observations of infrasound from Alaska and Antarctica: Mountain associated waves and geomagnetic/auroral infrasonic signals, in *Infrasound Monitoring for Atmospheric Studies*, Springer.
WMO, 2014. Weather & climate – understanding risks and preparing for variability and extremes, Tech. Rep. 2, WMO, doi: 10.1016/0377-0273(94)90038-8.
Wong, I., 2014. How big, how bad, how often: are extreme events accounted for in modern seismic hazard analyses? *Natural Hazards*, **72**(3), 1299–1309.
World Bank, 2011. The recent earthquake and tsunami in Japan: implications for East Asia, *East Asia and Pacific Economic Update*, **1**, Retrieved 23 November 2012; http://siteresources.worldbank.org/INTEAPHALFYEARLYUPDATE/Resources/550192-1300567391916/ EAP Update March 2011 japan.pdf.
World Bank, 2013. Development data group, ed. world development indicators 2013, World bank-free pdf, World Bank.
World Economic Forum, 2014. Global Risks 2014 – Ninth Edition, Tech. rep., World Economic Forum.
Zahran, S., Brody, S. D., Vedlitz, A., Grover, H., & Miller, C., 2008. Vulnerability and capacity: explaining local commitment to climate-change policy, *Environment and Planning C: Government and Policy*, **26**, 544–562, doi:10.1068/c2g.
Zaniboni, F. & Tinti, S., 2014. Numerical simulations of the 1963 Vajont landslide, Italy: Application of 1D Lagrangian modelling, *Natural Hazards*, **70**(1), 201e567–592.

Appendices

Appendix A: Glossary

Anthropogenic hazard:
a hazard resulting primarily from human actions or originating in the built environment. These include, but are not limited to, wars, terrorism, accidents, infrastructure failure, mismanagement of resources, and economic downturns. With increasing impact of human actions on the planet, the distinction between anthropogenic and natural hazards becomes less clear.

Disaster:
a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts.

Geohazard:
a hazard that involves geological processes at a wide range of spatial and temporal scales. In the context of this paper, the definition of geohazards is broad and covers all hazards that originate or interact with the solid Earth, including earthquakes, landslides, tsunamis, volcanic eruptions, floods, droughts, heat waves, and bolides.

Hazard:
a situation that poses a threat to life, health, property, or environment. In the context of this paper, the term hazard is also used to denote the incidence of hazardous events. In some scientific disciplines, hazard is defined as the probability of an event to occur. Here, we use hazard to denote a situation that would pose a threat if it occurred independent of the probability of its occurrence. Thus, a very large volcanic eruption is considered an extreme hazard, independent of the probability of the eruption actually occurring.

Natural hazard:
a hazard that is caused by a natural event. Besides geohazards as defined above, this includes, among others, storms, viruses, solar storms, and cosmic radiation.

Preparedness:
actions taken to plan, organise, equip, train, and exercise to build, apply, and sustain the capabilities necessary to prevent, protect against, ameliorate the effects of, respond to, and recover from climate-change-related damage to life, health, property, livelihoods, ecosystems, and national security.

Recurrence interval:
in the context of X-events, recurrence interval is used to refer to the likelihood of an event occurring at least once anywhere on Earth within the given period.

Resilience:
the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

Risk:
here the term is used to denote the value that is likely to be lost due to a hazard. It is the product of hazard probability, vulnerability of an exposed asset to the hazard, and the value of the asset.

Threat:
is the product of 'intent' and 'capability' to inflict harm. In the context of natural hazards, the intent is the probability of the event taking place, and the capability is the damage the event can cause.

Vulnerability:
here the term is used to denote a characteristic of an asset to experience damage if exposed to a hazard. The study of the vulnerability of human and natural systems to hazards is a relatively new interdisciplinary field, which is developing particularly with a view on climate effects and other natural hazards. A common language has not been developed yet, and experts from different field put different meanings to the terms used (e.g., Dolan & Walker, 2003). In particular, approaches differ between the natural and social sciences (e.g. Brooks, 2003).

X-event:
an event that is rare, surprising, and has potentially huge impacts on human life. An outlier outside the 'normal' region that could lead to "the collapse of everything" (Casti, 2012).

Appendix B: **Overview of Earthquakes in the Last 2,000 Years**

Table 8. Overview of known earthquakes during the last 2,000 years up to 2012.

Date	Location	Latitude	Longitude	Magnitude
19 May 526	Antioch, Turkey			8
22 December 856	Qumis, Iran	36.23	54.14	
13 July 869	Sendai, Japan	38.5	143.8	8.6
23 March 893	Ardabil, Iran	38.28	48.30	–
11 October 1138	Aleppo, Syria	36.1	36.8	11
20 September 1498	Honshu, Japan	34.0	138.1	8.6
23 January 1556	Shaanxi, China	34.5	109.7	8.2-8.3
16 December 1575	Valdivia, Chile	-39.8	-73.2	8.5
24 November 1604	Arica, Chile	-18.5	-70.4	8.5
20 October 1687	Lima, Peru	-15.2	-75.9	8.2
26 January 1700	Cascadia, North America			9
31 December 1703	Kanto Region, Japan	35.0	140.0	8.2
28 October 1707	Hoel, Japan	33.0	136.0	8.6
8 July 1730	Valparaiso, Chile	-32.5	-71.5	8.7
25 May 1751	Concepcion, Chile	-36.83	-73.03	8.5
1 November 1755	Lisbon, Portugal	36	-11	8.7
25 November 1833	Sumatra, East India (now Indonesia)	-2.5	100.5	8.8–9.2
13 August 1868	Arica, Chile	-18.50	-70.35	9.0
10 May 1877	Iquique, Chile	-19.6	-70.23	8.8
31 January 1906	Colombia–Ecuador	1	-81.5	8.8
28 December 1908	Messina and Reggio Calabria, Italy	38.3	15.6	7.2
16 December 1920	Ningxia-Gansu, China	36.6	105.32	8.6
11 November 1922	Atacama Region, Chile	-28.5	-70.0	8.5
3 February 1923	Kamchatka Peninsula, Russia	54	161	8.5
1 September 1923	Kanto Region, Japan	35.4	139.0	7.9

Appendix B: Overview of Earthquakes in the Last 2,000 Years

Fatalities	Notes
250,000	The city of Antioch was greatly damaged, and some decades later the city's population was just 300,000. Fire destroyed most of the buildings.
45,000-200,000	The city of Damghan was half destroyed and had 45,096 casualties.
~1,000	Triggered a tsunami which caused wide spread flooding of the Sendai plain.
150,000	
thousands	Triggered a large tsunami. The death toll associated with this event is uncertain, but between 26,000 and 31,000 casualties were reported.
830,000+	More than 97 counties in the provinces of Shaanxi, Shanxi, Henan, Gansu, Hebei, Shandong, Hubei, Hunan, Jiangsu and Anhui were affected. An 840 km wide area was destroyed, and in some counties 60% of the population was killed.
	Caused the subsequent flood of Valdivia due to river disruption.
~51-100	
5,000	Caused severe damage to Lima, Callao and Ica. It triggered a tsunami that killed most of the people.
	Triggered a tsunami that struck the coast of Japan.
5,233	Shook Edo and killed 2,300 people due to the shaking and subsequent fire. It triggered a major tsunami (10 m maximum in some areas) which increased the death toll to at least 5,233 but probably up to 10,000.
5,000+	Caused moderate to severe damage throughout Honshu, Shikoku and Kyushu. Triggered a tsunami (up to 10 m in some place), which resulted in more than 5000 casualties.
	Triggered a major tsunami that inundated the lower parts of Valparaiso. It caused damage from Serena to Chillan. Tsunami had a maximum run up height of 16 m.
~65	Destroyed the cities of Concepcion, Chillan, Cauquenes, Curico and Talca. Changed the course of the river some 15 blocks.
80,000	Caused fires and triggered a huge tsunami. Almost totally destroyed Lisbon and adjoining areas. According to http://tsun.sscc.ru/ttt_rep.htm 40,000 died due to tsunami.
numerous	Triggered a huge tsunami flooded all southern part of western Sumatra from Pariaman to Bengkulu. Also damage in the Seychelles.
25,000	A tsunami (or multiple tsunamis) in the Pacific Ocean was produced by the earthquake, which was recorded in Hawaii, Japan and New Zealand. 3,000 died by tsunami according to http://tsun.sscc.ru/ttt_rep.htm
2,541	Triggered a devastating tsunami. A total of 2,541 people died, mainly in Peru and what is now northernmost Chile, with some deaths also reported from Hawaii and Japan.
1,000	Triggered a destructive tsunami. The maximum recorded run-up height was 5 m in Tumaco, Colombia. At Hilo, Hawaii a 1.8 m run-up height was recorded for this event. The tsunami was also noted in Costa Rica, Panama, Mexico, California and Japan.
70,000	Reggio on the Italian mainland also suffered heavy damage. Moments after the earth-quake, a 12 m tsunami struck nearby coasts, causing even more devastation; 91% of structures in Messina were destroyed and some 70,000 residents were killed.
235,502	A landslide buried the village of Sujiahe in Xiji County. More than 30,000 people were killed in Guyuan County. Nearly all the houses collapsed in the cities of Longde and Huining.
100s	The earthquake caused extensive damage from Copiapo to Coquimbo. It triggered a destructive tsunami (max 7 m high) that caused significant damage to the coast of Chile and was observed as far away as Australia. The tsunami killed several hundred people in coastal cities, especially in Coquimbo.
	Triggered an 8 m tsunami that caused considerable damage in Kamchatka, with a number of reported deaths. The tsunami was still 6 m high when it reached Hawaii, causing at least one fatality.
143,000	Earthquake devastated Tokyo, the port city of Yokohama, surrounding prefectures of Chiba, Kanagawa, and Shizuoka, and caused widespread damage throughout the Kantō region. A tsunami with waves up to 10 m high struck the coast of Sagami Bay, Boso Peninsula, Izu Islands and the east coast of Izu Peninsula within minutes. The tsunami killed many, including about 100 people along Yui-ga-hama beach in Kamakura and an estimated 50 people on the Enoshima causeway. Over 570,000 homes were destroyed, leaving an estimated 1.9 million homeless. Tsunami and fire caused most deaths.

Appendix B: **Overview of Earthquakes in the Last 2,000 Years**

Date	Location	Latitude	Longitude	Magnitude
1 April 1946	Unimak Island, Alaska, United States.	52.75	-163.5	8.6
15 August 1950	Assam, Tibet	28.5	96.5	8.6
4 November 1952	Kamchatka, Russia	52.76	160.06	9
9 March 1957	Andreanof Island, Alaska, United States	51.56	-175.39	8.6
22 May 1960	Valdivia, Chile	-38.24	-73.05	9.5
13 October 1963	Kuril Islands	44.81	149.54	8.5
28 March 1964	Prince William Sound, Alaska, United States	61.02	-147.65	9.2
4 February 1965	Rat Island, Alaska, United States	51.21	-178.5	8.7
27 July 1976	Tangshan, China	39.61	117.89	7.6
26 December 2004	Sumatra, Indonesia, Indian Ocean	3.30	95.87	9.1
28 March 2005	Nias Region, Indonesia	2.085	97.108	8.6
12 September 2007	Sumatra, Indonesia	-4.517	101.382	8.5
12 January 2010	Port-au-Prince, Haiti	18.451	-72.445	7.0
27 February 2010	Maule, Chile	-35.84	-72.72	8.8
11 March 2011	Japan Region (Tohoku earthquake)	38.32	142.37	9.0
11 April 2012	Northern Sumatra, Indian Ocean	2.31 0.77	93.06 92.45	8.6 8.2

Appendix B: **Overview of Earthquakes in the Last 2,000 Years**

Fatalities	Notes
165 (due to low population density)	Triggered a pacific wide tsunami. 159 of the casualties occurred in Hilo, Hawaii. It obliterated Unimak island.
1,526	The earthquake was destructive in both Assam and Tibet, and 1,526 people were killed. Also the largest known earthquake to have not been caused by an oceanic subduction. Instead, this quake was caused by two continental plates converging.
~1,000 Sources vary widely	Triggered a large tsunami causing destruction and loss of life on the Kamchatka Peninsula. Impacted Hawaii causing US$1,000,000 damage, but no deaths. http://earthquakes.sciencedaily.com/l/3519/Russia-Kamchatka-Peninsula. According to http://tsun.sscc.ru/ttt_rep.htm there were more than 10,000 deaths caused by the tsunami.
0 (due to low population density)	Triggered a tsunami that reached 16 m and caused $5,000,000 in damage in Hawaii destroying two villages on Oahu. Death toll zero (http://tvnz.co.nz/world-news/world-s-biggest-earthquakes-since-1900-3384698).
5,700	Tremors caused landslides and triggered a major tsunami (26ft and 35ft) affecting southern Chile, Hawaii, Japan, the Philippines eastern New Zealand, southeast Australia, Aleutian island Alaska. Tsunami killed ~1,180 people in Chile according to http://tsun.sscc.ru/ttt_rep.htm.
	Triggered a 4.5 m tsunami.
125 (due to low population density)	Anchorage sustained great destruction or damage to many inadequately engineered houses, buildings, and infrastructure. Nearby, a 27-foot (8.2 m) tsunami destroyed the village of Chenega, killing 23 of the 68 people who lived there; survivors out-ran the wave, climbing to high ground. Post-quake tsunamis severely affected Whittier, Seward, Kodiak, and other Alaskan communities, as well as people and property in British Columbia, Oregon, and California. Tsunamis also caused damage in Hawaii and Japan.
0 (due to low population density)	Triggered a tsunami of over 10 m on Shemya Island and 2 m at Amchika Island but caused little damage. It was observed at Peru, Ecuador, Mexico, California, Japan and Eastern Russia.
242,419	More than half a month before the earthquake struck, Wang Chengamin of the State Seismological Bureau (SSB) Analysis and Prediction Department had already concluded that the Tangshan region would be struck by a significant earthquake between July 22, 1976 and August 5, 1976
230,000-3000,000	Most people died due to the huge tsunami created.
1,303	Triggered a small tsunami. Most people were killed by the earthquake (1300).
25	Many buildings collapsed on the west coast of Sumatra. At least 25 dead, and over a hundred injured. Tsunami alert issued for the entire Indian Ocean Region but tsunamis were small. Max 1 m.
230,000-316,000	Worst earthquake in region in 200 years.
523	Triggered a tsunami which devastated several coastal towns in south-central Chile and damaged the port at Talcahuano. Minor damage in San Diego, California.
15,870	Triggered a huge tsunami. Centred closest to Enoshima, Miyagi, at a depth of 32 km. Most damage occurred in Sendai. Damage occurred in Fukushima, Iwate and Miyagi due to tsunamis. Tsunami reached height of 40.5 m in Miyako. Travelled up to 10km inland in the Sendai area. Earthquake moved Honshu (the main island) 2.4 m east and shifted the Earth figure axis by estimated 10 cm to 25 cm.
10	Centred 434 km SW of Banda Aceh, Sumatra, Indonesia, at a depth of 22.9 km. Centred 618 km SSW of Banda Aceh, Sumatra, Indonesia, at a depth of 16.4 km. 10 dead due to heart attacks and shock. Triggered only small tsunamis.

Appendix C: Declaration on Extreme Geohazards and the Reduction of Disaster Risks

Preamble

Geohazards such as earthquakes, landslides, volcano eruptions and associated tsunamis and floods cause large and increasing loss of lives and property. Most of these losses occur during high-impact, extreme events. The global and long-lasting societal and economic impacts of recent extreme events illustrate the scale of disasters that can be caused by geohazards, and remind us of the challenge of extreme events for disaster risk management. At the same time, the recent major geohazards causing disasters with global impacts are dwarfed by the largest geohazards that occurred during the last few millennia. The potential impact on our civilisation of any such rare event tends to be ignored in planning of land use, infrastructure, and socio-economic processes. The recent extreme disasters revealed gaps in the knowledge of geohazards available to policy- and decision-making. Understanding the full spectrum of geohazards, including the extreme events, is a prerequisite for disaster risk management and increased global resilience to these events. Reducing the disasters induced by the occurrence of extreme hazards at an acceptable economic cost requires a solid scientific understanding of the hazards. The current understanding of high-impact geohazards and the challenges posed to the disaster risk management cycle were reviewed during the European Science Foundation (ESF)–European Cooperation in Science and Technology (COST) high level research conference on 'Understanding Extreme Geohazards: The Science of the Disaster Risk Management Cycle', held on November 27 – December 2, 2011 in Sant Feliu de Guixols, Spain.

The participants of this conference recognise the work done by the international geohazards community and, in addressing the needs identified in the declaration, intend to build on this work, in particular on the 2007 Frascati Declaration of the Third International Workshop on Geohazards; the Road Map of the Geohazards Community of Practice (GHCP) of the Group on Earth Observations (GEO) developed in 2010, and the progress made since then.

Recognising that:

- Major research efforts have been made to understand the causes and processes of geohazards;
- Significant advances have been achieved in our knowledge of the hazardous areas, and many measures required to prepare for, and adapt to, hazards have been developed;
- International programmes informing governments, decision makers, and the general public on disaster risks, and ways to reduce these risks, are being conducted;

Realising that:

- The loss of lives and properties through natural hazards, particularly geohazards, is rapidly increasing due to a growing population expanding into hazardous areas;
- The direct and indirect consequences of extreme events are likely to increase as more population and infrastructure is put in harm's way and the interconnectivity of global society increases;
- Few options exist to reduce geohazards, but exposure and vulnerability can be reduced by properly choosing where to build and how, and by adapting existing buildings to potential hazards;
- Proper planning of land use, particularly in rapidly growing urban areas, is key to risk reduction;
- The failure to significantly reduce the impacts of geohazards on society is partially due to a gap between science and research programmes and the communities in harm's way; this gap also extends to many national, regional, and local decision makers;
- Disaster risk reduction rarely happens in communities suffering from poverty, high levels of corruption, or opaque decision making;
- Adaptation to geohazards is hampered by an inadequate and inaccurate perception of the risks and a lack of publicly available and easy to understand, information;
- Research in the traditional academic disciplines faces structural challenges that discourage research projects integrating the natural and social sciences, disaster management professionals and planners, and the community exposed to the hazards;
- In many regions, rules, laws, and legislation facilitating a safe built environment are either absent, or enforcement is hampered by organisational obstacles, including corruption;
- A large fraction of the death toll in disasters caused by geohazards is due to delayed or inefficient response and rescue;

Emphasising the importance of the contributions of many international programmes and organisations, in particular that:

- The United Nations Educational, Scientific and Cultural Organization (UNESCO) aims to strengthen the role of science in disaster risk reduction through continued support of increasingly interdisciplinary inter-national research projects which include capacity building for team members and science education for the affected communities;

- The Hyogo Framework for Action (2005–2015) facilitates the implementation of measures to increase the resilience of nations and communities to disasters;
- The Group on Earth Observations (GEO) aims to provide the monitoring required to understand the natural hazards and to detect hazardous events in a timely manner;
- The Geohazards Community of Practice of GEO is developing the building blocks informing the four phases of the risk management cycle; i.e. preparedness, early warning, response, and recovery;
- The United Nations Office for Project Services (UNOPS) is developing natural disaster management units blending research, monitoring, capacity building and education;
- The Integrated Research on Disaster Risk (IRDR) Scientific Programme of the International Council of Science (ICSU) co-sponsored by the International Social Sciences Council (ISSC) and the United Nations International Strategy for Disaster Reduction (UNISDR) is developing the scientific basis for risk reduction measures;
- Several international scientific unions, including the International Geographical Union (IGU), the Inter-national Society for Photogrammetry and Remote Sensing (ISPRS), the International Union of Geodesy and Geophysics (IUGG), and the International Union of Geological Sciences (IUGS), promote basic research on geohazards, georisk, and sustainability via innovative multi- and trans-disciplinary research and outreach projects;
- The ESF has been facilitating a number of high level science conferences improving our understanding of the causes of disasters due to natural hazards;

We, the participants of the ESF-COST High-Level Research Conference on 'Understanding Extreme Geohazards: The Science of the Risk Management Cycle', declare the need that:

- A focused interdisciplinary research effort be made to increase our understanding of the nature of extreme geohazards and to improve our ability to assess their potential locations, intensity, and recurrence;
- A sustained geohazard monitoring system be implemented to provide observations for research, detection of hazardous events, and in support of disaster prevention, response and recovery;
- Data relevant to the monitoring and understanding of geohazards be shared freely in support of geohazard research and disaster risk reduction;
- Interdisciplinary research programmes be developed which integrate the natural and social sciences to address all phases of the disaster risk management cycle;
- A dedicated outreach and education programme be developed to support a change in the citizens' and authorities' perception of the risks associated with major geohazards and to help recognise the challenges these hazards pose to society;
- Organised efforts and resources be dedicated to education at the local level, particularly in developing countries, where community-based educational programmes are effective ways to empower those in harm's way to protect themselves from geohazards;
- Information on geohazards be disseminated so that relevant governmental bodies and citizens can make informed and transparent decisions on where to build what and how, and where to reduce the vulnerability of existing buildings to future hazards;
- State-of-the-art products be developed to help policy makers developing legislation for risk reduction and planning for a safe built environment;
- Preparedness and mitigation measures be tailored to specific local vulnerabilities, available resources, and social, cultural and religious constraints;
- International collaboration with local experts be fostered, to help regions with poorly developed governance mitigate disaster risks;
- Low-technology response and rescue capabilities be improved, particularly in developing countries, so that disaster-impacted populations can be reached more rapidly;
- A community-based white paper, addressing the scientific and societal challenges of increasing disaster risk due to extreme geohazards, be prepared and distributed to funding agencies and governmental and intergovernmental bodies;
- A process for an integrated assessment of disaster risk due to geohazards be established and the results of this assessment be articulated through an authoritative scientific body (such as the IPCC).

European Science Foundation
1 quai Lezay-Marnésia • BP 90015
67080 Strasbourg cedex • France
Tel: +33 (0)3 88 76 71 00
Fax: +33 (0)3 88 37 05 32
www.esf.org

April 2015 – Print run: 1000
Graphic design: Dans les villes, Strasbourg