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Global risk from extreme geophysical events: threat identification and assessment

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In an increasingly interconnected world, any single geophysical hazard is capable of having consequences far beyond the range of immediate physical effects. Most recently, this was demonstrated by the 2004 Asian tsunami, which took the lives of citizens from 57 different nations, and by Hurricane Katrina in August 2005, which raised fuel prices worldwide and contributed to a record UK trade deficit in the month following the devastation of New Orleans. On an altogether wider scale, global geophysical events (GGEs) are natural phenomena capable of having wholesale deleterious consequences for the world's environment, economy and society. These may arise (i) due to a global physical effect, such as an episode of severe planetary cooling in response to a volcanic 'super-eruption' or large comet or asteroid impact, or (ii) as a result of subsidiary ramifications for the global economy and social fabric of a cataclysmic regional event, such as an Atlantic- or Pacific-wide 'mega-tsunami', or a more spatially confined event at a strategically sensitive location, for example the awaited major Tokyo earthquake. While very infrequent, the wide-ranging—and potentially ruinous—consequences of a GGE for the well-being of the international community make it essential that they are seriously considered within any comprehensive assessment of natural threats.

Keywords: global geophysical event; super-eruption; mega-tsunami; asteroid impact; earthquake

1. Introduction

Global geophysical events (GGEs) are commonplace natural phenomena writ large (McGuire in press). Except within the contexts of scale and extent, the processes and mechanisms that underpin them, and their physical effects and consequences, are no different from the geophysical phenomena—whether windstorm, flood, volcanic eruption, earthquake or tsunami—that trigger natural disasters many times every year. GGEs are low frequency–high consequence geophysical phenomena capable of having wholesale deleterious ramifications for the environment and society. Both the frequency and the size may vary according to the phenomenon under consideration. Broadly speaking, however, frequency ranges from 10^2 to 10^8 years and the size from local through regional to global. The adverse remote consequences of a GGE may range from disruptive to

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Table 1. Summary of terrestrial, sudden-onset GGEs (age and frequency data from Decker 1990; Chesner 1998; Christiansen 2001; McGuire *et al.* 2002; Oppenheimer 2003*a*; Mason *et al.* 2004; McMurtry *et al.* 2004; Stuart & Binzel 2004). (Modified from McGuire in press.)

GGE type	selected past occurrences (ages: years before present, except where indicated)	identified future threats location/ region (selected)	estimated event frequency (years)
1 km asteroid impact	Zhamanshin (Kazakhstan) 0.9×10^6; Eltanin (Southern Ocean marine impact) 2.15×10^6	NEA AD 1950 (1 in 300 chance of impact; 16 March 2880)	6.0×10^5
volcanic super-eruption	Yellowstone, US (0.64×10^6 and 2.1×10^6) Toba, Indonesia (7.35×10^4)	Pacific rim and Southeast Asia	$\geq5\times10^4$
ocean-island volcano collapse and tsunami	Mauna Loa, Hawaii (1.20×10^5)	Hawaii, Canary and Cape Verde archipelagos	$\sim10^4$
climate-perturbing volcanic eruptions	Baitoushan, China AD 1030, AD 1259 (location unknown); Laki, Iceland AD 1783; Tambora, Indonesia AD 1815	?	250–1000
strategic earthquake	Tokyo (Japan) AD 1923	Tokyo	20–500

catastrophic and may arise (i) from a global physical effect, such as an episode of planetary cooling in response to a so-called volcanic super-eruption or large asteroid or impact, or (ii) as a result of subsidiary ramifications for the global economy and social fabric of a cataclysmic regional event, such as an Atlantic- or Pacific-wide ‘mega-tsunami’, or a more spatially restricted event at a strategically sensitive location, for example a major earthquake striking Japan’s Greater Tokyo metropolitan region.

While the aforementioned GGEs are sudden-onset events, this is not a required diagnostic attribute. Discrete, but slower-acting phenomena, such as the great flood-basalt outpourings of the Siberian (Russia) and Deccan (India) lava traps also qualify, as indeed does contemporary climate change, which can reasonably be regarded as currently the most threatening of all GGEs. Climate change is, however, too great and complex an issue to be considered with justice here. Instead I focus on identifying those sudden-onset GGEs that present a danger to our society and assessing the degree of the threat that faces us (table 1).

2. Global geophysical events in Earth history and human experience

Global geophysical events are only considered exceptional when set against the human lifespan or the length of recorded history. Within a geological time frame, they are neither anomalous nor unprecedented. Frequencies do, however, bridge an enormous range and vary by seven orders of magnitude from 10^2 years for earthquakes in strategically sensitive locations to 10^8 years for asteroid or comet impacts in the 10 km size range, and major flood-basalt outpourings. For the

Table 2. Impact frequencies of near Earth objects proposed by Stuart & Binzel (2004).

impactor size (m)	impact frequency (10^3 years)
40–50	2–3
∼200	56 ± 6
1000	600

purposes of this paper, the latter events are disregarded as being too infrequent to present realistic threats on a time-scale that has any relevance for contemporary hazard and disaster management. At shorter time-scales, the frequency of 1 km (and smaller) impacts has recently been estimated as 6×10^5 years (Stuart & Binzel 2004; table 2), while return periods of volcanic super-eruptions may be as short as $4.5–5\times10^4$ years (Decker 1990; Mason *et al.* 2004). Giant (mega-) tsunamis triggered by the catastrophic flank failure of ocean-island volcanoes (e.g. Ward & Day 2001) may have time-averaged frequencies as low as 10^4 years, while factoring in the occurrence of colossal submarine landslides (e.g. Maslin *et al.* 2004) may reduce the frequency of giant tsunamis even further.

Owing to sub-micrometre dust loading of the stratosphere (e.g. Toon *et al.* 1994), large (*ca* 2–3 km) impacts have the potential to severely affect society and the environment through triggering a period of pronounced global cooling, lasting for several years, and commonly referred to as a *cosmic winter*. Similarly, blanket sulphate loading of the stratosphere following volcanic super-eruptions has been held responsible for comparable *volcanic winters* (Rampino *et al.* 1988). While the 'footprint' of physical effects arising as a consequence of a large impact or super-eruption could be expected to be essentially global, that associated with an ocean-wide giant tsunami would be confined to the margins of those nations bordering the affected ocean basin. In all cases, the degree of immediate destruction, damage and disruption would attenuate with increasing distance from the hazard source, but have massive impacts on the economy and social well-being of the international community. While smaller, in terms of the area directly affected, the extent of physical destruction due to an ocean-wide giant tsunami is likely to be larger than that arising from a large impact or super-eruption.

Smaller-scale or lower-intensity GGEs have destruction and damage potentials orders of magnitude less than those of large impacts, super-eruptions and mega-tsunamis, but remain capable of serious impacts on global society as a consequence of knock-on effects on the world's environment or economy. These include climate-perturbing volcanic eruptions (e.g. Oppenheimer 2003*a*,*b*) that fall short of super-eruption status, and catastrophic earthquakes that strike at the heart of a G8 economy (Rikitake 1991; Bendimerad 1995; Stein *et al.* 2006).

The high and increasing level of interconnectivity that has resulted in the growth of our 'global village' has substantially raised the degree of interdependence of nation states and trading blocks, in turn making the planetary economy and social fabric more susceptible to natural catastrophes at the top end of the scale. This is well illustrated by the December 2004 Asian tsunami, which took the lives of citizens from 57 countries. More recently, in

August 2005, the US$ 3.2 billion of insured losses sustained by Lloyd's of London as a consequence of the devastation of New Orleans by Hurricane Katrina, contributed, the following month, to the UK's largest ever trade deficit.

Geophysical phenomena sufficiently large to trigger worldwide problems today may have had relatively minor consequences in the insular, disconnected, subsistence societies of even a few centuries ago. Nevertheless, observations, records and accounts, some more plausible than others, do exist in support of catastrophic geophysical events occurring in the last several millennia that have the potential to be massively disruptive should they recur. These provide us with some constraint on return periods of those GGEs that are more frequent. For example, serious climate-perturbing volcanic eruptions occurred in both 1783 (Laki, Iceland; Grattan & Pyatt 1999; Grattan *et al.* 2003) and 1815 (Tambora, Indonesia; Oppenheimer 2003*a*), while comparable events occurred at Baitoushan volcano (North Korea–China border) in AD 1030 and at unidentified locations in AD 450 and 1259 (Oppenheimer 2003*a*,*b*). Going back further, Nur & Cline (2000) have proposed that groups of major earthquakes, or 'earthquake storms', shook the Aegean and eastern Mediterranean regions during the late thirteenth and early twelfth centuries BC, with catastrophic consequences for Late Bronze Age civilizations. Still further back in time, Baillie (1999) postulated, on the basis of tree-ring data, major, climate-perturbing volcanic eruptions in 3195 BC, 2354–2345 BC and possibly 2911 BC. Others have proposed bombardment from space in early human history, by impactors that were small (less than 500 m), yet large enough to load the atmosphere with sufficient dust to affect global temperatures. For example, Clube & Napier (1990) put forward the idea that swarms of small Bronze Age impacts arose from a collision between the Earth and fragments of a disrupted comet, while Steel (1995) also speculates upon a possible series of impacts around 5000 years BP.

3. Asteroid and comet collisions and the global threshold

While the occurrence of asteroid or comet strikes within the time-scale of human experience remains a matter for debate, there is no doubt that such impacts were commonplace in Earth history. Similarly, collisions with larger (greater than or equal to 10 km) objects have been responsible for causing or contributing to a number of mass extinctions (e.g. Rampino *et al.* 1997). Detailed assessment of the contemporary impact threat is discussed elsewhere (Morrison 2006), so here I concentrate briefly on summarizing those research issues that relate most closely to impacts as GGEs. In terms of quantifying the risk posed by impacts to our civilization, two parameters are particularly important: (i) the lowest size limit of an impactor (the *global threshold*) capable of causing a catastrophic fall in global temperatures (the *cosmic winter*) and (ii) the frequency of such events. Until very recently, the global threshold was set at around 1 km, and such objects were estimated to strike the Earth once every 10^5 years, leading, in a future collision, potentially to over 10^9 deaths, mainly through famine (Chapman & Morrison 1994). Addressing impact frequencies of near Earth objects, however, Stuart & Binzel (2004) estimate that 1 km impacts should only be expected every 6.0×10^5 years (table 2). This is at variance with the impact catalogue, which

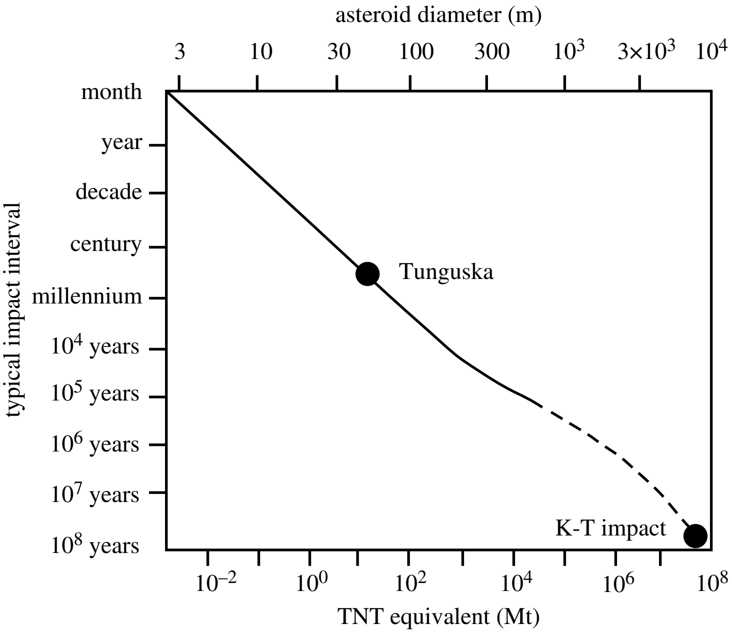


Figure 1. Cumulative energy–frequency curve for impacts on the Earth, also showing asteroid diameters (from Chapman & Morrison 1994).

records three impacts of 1 km or larger in the last 4 million years on the 15% of the planet's surface that is capable of retaining the evidence; translating to a global 1 km impact frequency closer to the original 10^5 years estimate and a higher level of risk. As of 21 March 2006, however, 831 large (greater than or equal to 1 km) near Earth asteroids (NEAs), out of a predicted population of 1100 ± 200 (Chapman in press), have been identified. All have been ruled out as presenting a threat in the foreseeable future, meaning that our exposure to a large impact (at least from the NEA population) has been dramatically reduced. A further reduction will follow should NASA achieve its goal of locating 90% of large NEAs by 2008.

In addition to questions over the frequency of large impacts, there are also doubts about the effectiveness of such events in reducing global temperatures via atmospheric dust attenuating incoming solar radiation. Toon *et al.* (1994) identifies 10^5 Mt (TNT equivalent; figure 1) as the energy for impacts in land targets, at which sub-micrometre dust yields an atmospheric opacity approaching 1 (figure 2), which he notes is comparable to that produced by very large explosive volcanic eruptions. This energy yield is of the order of that expected from a 1 km impact. According to Chapman (in press), an impact on this scale would have the potential to affect the global climate, but a larger impact in the 2–3 km size range would be required to trigger a multi-year *cosmic winter*, and the degree of death, destruction and economic and social breakdown required to seriously threaten modern civilization. With impacts of 2 km expected every 2×10^6 years, the potential for an impact event to qualify as a GGE is much reduced, with a probability of occurrence up to 40 times lower, for example, than a super-eruption of comparable effect. In the context

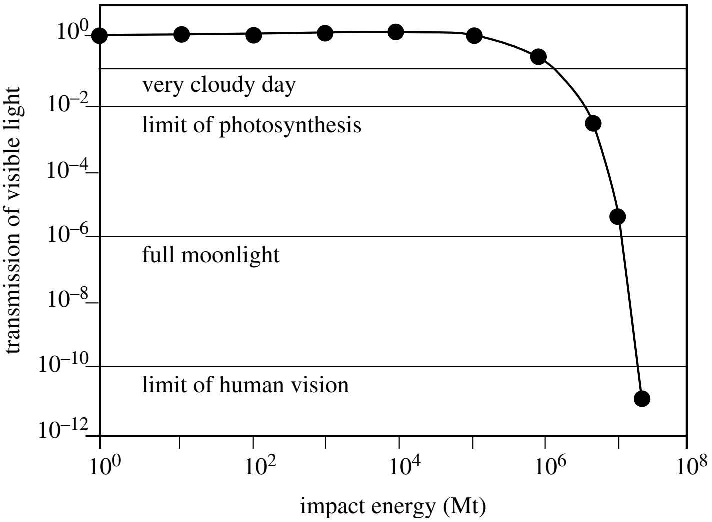


Figure 2. Light transmission reduction resulting from the injection of sub-micrometre dust into the atmosphere following impacts of various energies. 10^5 Mt (TNT equivalent) is the threshold energy (for impacts in land targets), for which global effects due to cooling are likely to begin to become apparent (from Toon *et al.* 1994).

of global consequences, the 'global threshold' is an arbitrary and weakly defined limit that does not relate to a specific global temperature fall. It can reasonably be argued that impacts smaller than 1–2 km may lead to less than catastrophic but still significant temperature falls, with serious consequences for society and the environment.

4. Volcanic global geophysical events in context

Volcanic events affect the world's climate far more frequently than asteroid or comet impacts. In particular, major explosive eruptions are capable of modifying the Earth's climate through the release of large quantities of sulphur gases capable of mixing with atmospheric water to form stratospheric aerosol clouds. The level of solar radiation reaching the troposphere and the Earth's surface is significantly reduced by volcanic aerosol clouds. In the last quarter of a century alone, two eruptions, at El Chichon (Mexico) in 1982 and Pinatubo (Philippines) in 1991, have had a measurable cooling effect worldwide. Going further back, eruptions at Laki (Iceland) in 1783 and Tambora (Indonesia) in 1815, both had major, deleterious impacts on, respectively, the regional and global climate. The Tambora eruption was the largest known historic eruption (Oppenheimer 2003*a*), but even this may be regarded as a minor volcanic event in comparison with the 7.35×10^4 years BP 'super-eruption' of Toba (Sumatra, Indonesia; Chesner *et al.* 1991). The term *super-eruption* has become synonymous with volcanic events registering a score of 8 on the semi-quantitative, logarithmic, volcanic explosivity index (VEI; Newhall & Self 1982). A VEI 8 eruption is defined as one that ejects 10^3 km^3 or more of material. As this does not take account of the density of the ejecta, however, a more useful measure is that proposed by Mason *et al.* (2004), who define the largest known explosive

Table 3. Likelihood of future large magnitude eruptions, assuming homogeneous Poisson behaviour (from Mason *et al.* 2004). (A frequency of 1.4 events per 10^6 years corresponds to the known (minimum) large eruption rate since 1.35×10^7 years BP; 2 events per 10^6 is approximately the known large eruption rate from 2.5 to 3.6×10^7 years BP, and for the period 0–6×10^6 years. A frequency of 22 events per 10^6 years is the upper bound determined by extreme value analysis.)

	frequency		
eruptions of magnitude 8 and larger	1.4 events per Myr	2 events per Myr	22 events per Myr
probability of ≥1 event in next 100 years (%)	0.014	0.02	0.2
probability of ≥1 event in next 10^6 years (%)	75	86	100
time for 1% chance of an eruption (years)	7200	5000	460
time for 95% probability of an eruption (10^6 years)	2.1	1.5	0.14

eruptions as those that eject greater than or equal to 10^{15} kg of material, and allocate *magnitude* 8 and 9 labels to these events on a logarithmic scale based on erupted mass rather than volume.

5. Super-eruption frequencies and characteristics

Mason *et al.* (2004) identify 47 events with masses of 10^{15} kg or more, 42 of which occurred in the last 3.6×10^7 years and five in the last 2×10^6 years. The latter include two VEI 8 eruptions at Yellowstone (Wyoming, USA)—2.1×10^6 and 0.64×10^6 years BP (Smith & Braile 1994; Christiansen 2001)—along with those of Toba and Oruanui (Taupo, New Zealand), the most recent super-eruption dated at 2.65×10^4 years BP (Wilson 2001). Frequency figures determined by Mason *et al.* (2004) for a magnitude 8 event are wide ranging, from 1.4 to 22 every 10^6 years. Assuming Poisson behaviour, this translates into at least a 75% probability of a magnitude 8 eruption within the next 10^6 years and a 1% chance of a magnitude 8 eruption in the next 4.6×10^2–7.2×10^3 years (table 3).

Little is known about the majority of the 42 cataclysmic eruptions catalogued by Mason *et al.* (2004) and the most closely studied are those that occurred at Yellowstone (figure 3), Toba and Oruanui. Invariably, explosive eruptions on this scale involve siliceous, high-viscosity rhyolitic magma and result in the formation of large calderas. Both the Yellowstone (Lowenstern *et al.* 2006) and Toba (Self 2006) caldera systems remain active and *restless* and are characterized by continuing hydrothermal activity, seismicity and surface deformation. The formation of the large volumes of rhyolitic magma required to feed a super-eruption necessitates the involvement of similarly silica-rich continental crust in magma formation and spatially limits such volcanic systems to ocean–continent destructive plate margins (e.g. Toba) and continental mantle plume settings (e.g. Yellowstone). During super-eruptions, magma is commonly ejected from ring fractures that during the later stages of the eruptions act as faults, along which a central crustal block subsides to form a caldera. Magma is expelled in the form of curtain-like eruption columns that may persist for up to two weeks (Ledbetter & Sparks 1979), and which can carry tephra to altitudes of 40 km or more. Column collapse typically results in

Figure 3. Yellowstone (USA) has experienced three colossal, caldera-forming eruptions, two of which qualify as super-eruptions: 2.1×10^6 and 0.64×10^6 years BP. The caldera system remains ‘restless’.

the formation of extensive pyroclastic flows that deposit *ignimbrite* (pumice-rich material) over areas of the order of 10^4 km^2 or more. While the coarser tephra component falls to Earth locally, progressively finer fractions are deposited over an area the size of a continent, with the finest material being distributed globally by stratospheric winds. However, the lower limit of a super-eruption is defined either as 10^{15} kg or 10^3 km^3. Masses and volumes can be far greater, with the 2.1×10^6 years BP eruption at Yellowstone ejecting around 2.45×10^3 km^3 (5.4×10^{15} kg) of debris and the 7.35×10^4 years BP Toba event expelling at least 2.8×10^3 km^3 (6.9×10^{15} kg) of material.

6. The Toba super-eruption

The Toba super-eruption of 7.35×10^4 years BP (Chesner *et al.* 1991) is the most closely studied, both in terms of its geology (Chesner 1998) and its environmental impact (e.g. Rampino & Self 1992, 1993*a*; Bekki *et al.* 1996; Yang *et al.* 1996; Zielinski *et al.* 1996). Research has, however, been hindered to some extent by political instabilities in northern Sumatra and a number of important eruption parameters remain poorly constrained. In particular, the sulphur yield of the eruption remains uncertain. On the basis of the mineral chemistry of the younger Toba tuff deposited by the eruption, Rose & Chesner (1990) propose a value of 3.3×10^{12} kg S. In contrast, Zielinski *et al.* (1996) estimate, from volcanic sulphate recorded in the Greenland Ice Sheet Project 2 (GISP2) Greenland ice core, a figure of $0.57–1.1\times10^{12}$ kg S. Through extrapolating experimental data, Scaillet *et al.* (1998) suggest the far lower value of 3.5×10^{10} kg S. While the higher sulphur yields are of the order or 20 times that of the 1815 eruption of Tambora, the Scaillet *et al.* (1998) estimate is just three times the sulphur yield of the 1991 Pinatubo (Philippines) eruption. This lower figure has led Oppenheimer (2002) to question both the scale and consequences of the episode of global cooling resulting from the Toba eruption.

For an aerosol loading of 10^{12} kg, and scaling up from the observed 0.7 °C temperature fall caused by the Tambora event, Rampino & Self (1992, 1993*a*) concluded that the Toba eruption triggered a 3–5 °C Northern Hemisphere temperature fall. More recently, the climatic impact of a generic super-eruption has been simulated using the coupled ocean–atmosphere model of the UK Met Office (Jones *et al.* 2005). The results show a near-surface global temperature fall as high as 10 °C for several months, with temperatures deviating considerably from normal for several decades. In addition, global precipitation falls by a third, and the thermohaline ocean circulation doubles in intensity, modifying regional temperature patterns in the Northern Hemisphere. Although the model predicts that snow and ice extent will increase to a maximum 35% coverage of the Earth, it does not reveal any longer-term climate changes capable of leading to ice age-like conditions.

The length of the *volcanic winter* triggered by the Toba event is not well constrained, but assuming an *e-folding* stratospheric residence time for the Toba aerosols of about 1 year, Rampino & Self (1992) suggest that it could have lasted for several years. In support of this, a *ca* 6-year-long period of volcanic sulphate deposition recorded in the GISP2 ice core at about the time of the Toba eruption suggests that the residence time of the Toba aerosols may have been of this order (Zielinski *et al.* 1996). This is corroborated by modelling undertaken by Bekki *et al.* (1996), which suggests that SO_2 aerosol levels in the stratosphere would have been above background for nearly a decade. Zielinski *et al.* (1996) recognized a 1000-year-long cooling episode—prior to Dansgaard–Oeschger event 19 (a warm *interstadial around* 7×10^4 years BP)—and immediately following the deposition in the ice of the Toba sulphate. They suggest that the longevity of the Toba stratospheric loading may account at least for the first two centuries of this, which is in reasonable agreement with the results of the Hadley Centre simulation (Jones *et al.* 2005).

The impact on our human ancestors of such an extended period of volcanogenic cooling remains a matter for speculation, although Rampino & Self (1993*b*) have made a link with a putative Late Pleistocene human population crash that may have reduced the race to a few thousand individuals. More recently, Rampino & Ambrose (2000) have invoked the Toba eruption to explain a severe culling of the human population, from the survivors of which the modern human races differentiated around 7×10^4 years BP. While the ability of a single volcanic eruption, however large, to dramatically influence the evolutionary development of the human race remains controversial, a similar effect has also been proposed for the much smaller (*ca* 200 km^3) Campanian Ignimbrite eruption in the Bay of Naples region of Italy (Fedele *et al.* 2002).

7. Smaller climate-perturbing eruptions and their effects

Volcanic eruptions capable of producing global effects are not required to have average return periods measured in millennia or tens of millennia. Most notably, a number of large volcanic eruptions during the last 1500 years, while falling far short of super-eruption status, have had a significant effect on regional or global weather and climate. By far the best known and studied is the 1815 eruption of Tambora (Sumbawa island, Indonesia), which is held responsible for 1816 being a *year without a summer* in Europe and North America. The Tambora blast scores 7 on the VEI, and is estimated to have ejected around 7.8×10^{13} kg of debris (Self *et al.* 2004). The eruption's climatic impact arose from the injection of perhaps 60 Mt of sulphur into the stratosphere, around six times more than was released by the 1991 Pinatubo (Philippines) eruption (Oppenheimer 2003*a*). The resulting sulphate aerosol veil led to significant climate perturbations, with unusually cold weather the following year affecting Europe, eastern Canada and the northeast US. Among other effects, the aftermath of the eruption is blamed for widespread crop failures, livestock deaths and major typhus epidemics, and the events of 1816 have been described as the western world's *last great subsistence crisis* (Post 1977). Estimates of the frequency of such climatically disruptive eruptions vary from 250–500 years (Decker 1990) to 500–1000 years (Oppenheimer 2003*a*). Certainly, an event comparable in magnitude occurred in AD 1030 at Baitoushan volcano on the border between North Korea and China (Oppenheimer 2003*a*). A major volcanic eruption is postulated as the cause of a serious climate perturbation around AD 540 (Keys 2000), and the most prominent sulphate layer (four times the magnitude of the Tambora signal) in the GISP2 Greenland ice core record for the last 7×10^{3} years (Zielinski 1995) testifies to a huge, but as yet unidentified, eruption in AD 1259. On a more localized scale, the Laki (Iceland) effusive eruption of 1783, which extruded 14.7 km^3 of basalt and generated 122 Mt of sulphur dioxide, resulted in a serious perturbation of the European climate, alongside severe atmospheric pollution and noticeably elevated mortality rates in the UK and Europe (e.g. Grattan & Pyatt 1999; Grattan *et al.* 2003; Witham & Oppenheimer 2005).

Clustered volcanic events that together elevate stratospheric sulphate aerosol loading may also conspire to perturb the global climate. Both Free & Robock (1999) and Crowley (2000) propose that the medieval cold period known as the *Little Ice Age* can be explained in terms of multiple volcanic eruptions significantly raising the mean optical depth of the atmosphere over a period long enough to cause decadal-scale cooling.

8. Trans-oceanic 'mega-tsunamis'

Most trans-oceanic tsunamis are triggered by major ($M_w \geq 9.0$) earthquakes. These occur several times a century, most recently in 1960 (Chile), 1964 (Alaska) and 2004 (Sumatra). The Chile event triggered tsunamis that were 3–4 m high when they struck Japan, while run-up heights of 4 m were also recorded on the East African coast following the December 2004 Sumatra earthquake. No strict definition exists for the term 'mega-tsunami', which is essentially a media-driven descriptor. An arbitrary definition, suggested here, reserves the term for waves that are in excess of 100 m in height at source, and which remain destructive at oceanic distances. No such event has been observed or reported in historic time or incontrovertibly detected in the geological record. The great ($M_w \sim 9$) Cascadia (western North America) earthquake of 1700 generated Pacific-wide tsunamis, but these appear to have been of the order of 3 m high at shore in Japan (Satake *et al.* 1996). Around 8200 years ago, the formation of the massive (3×10^{3} km^3) Storegga submarine sediment slide off the coast of Norway (e.g. Dawson *et al.* 1988; Bugge *et al.* 1988; Masson *et al.* 2006) triggered tsunamis with

Table 4. Estimated radius from impact of a tsunami with 10 m height at shore (Crawford & Mader 1998).

	run-up factor			
impactor diameter (m)	5	10	20	40
50	10	20	40	60
100	40	70	130	230
200	140	250	460	820
500	800	1400	2500	4400
1000	2800	5000	9000	16 000

run-up heights in excess of 20 m at distances of around 400 km, but these attenuated rapidly to just a few metres at 700–800 km from the source (e.g. Bondevik *et al.* 2005). The Japanese wave run-up estimates arising from the last major ($M_{\mathrm{w}} \sim 9$) Cascadia earthquake suggest that seismogenic triggering of a mega-tsunami—as arbitrarily defined here—is probably not feasible. This leaves two possibilities: impacts in the marine environment and wholesale lateral collapses at ocean-island volcanoes. With respect to impacts, Crawford & Mader (1998) argue that only large impactors are capable of mega-tsunami formation. They propose that the 'hole' generated at impact must be 3–5 times the ocean depth in order to result in the formation of a coherently propagating wave. If the 'hole' is 20 times the diameter of the impactor and a typical ocean depth is 4 km, then a 1 km or greater object is required (Crawford & Mader 1998). Given that the frequency of 1 km impacts has recently been estimated at 6×10^5 years (Stuart & Binzel 2004), the likelihood of such an event is very small. Crawford & Mader (1998) estimate, on this basis, that even a coastal city located in a setting favouring a very high (×40) run-up factor (multiplier of the deep-sea wave height; table 4) should only be struck by a 10 m tsunami every 1.9×10^5 years.

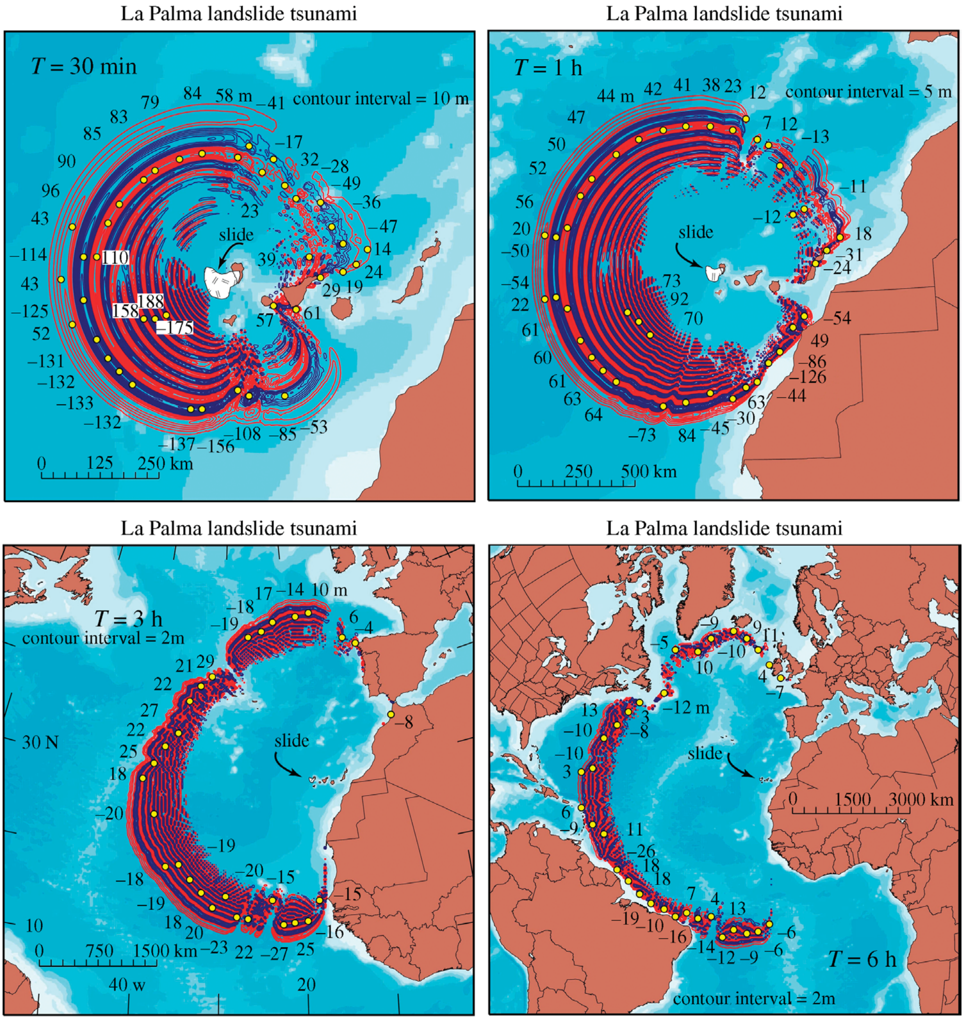
9. Ocean-island volcanoes as mega-tsunami sources

Landslides arising from the lateral collapse of ocean-island volcanoes (Keating & McGuire 2000, 2004) are among the biggest catastrophic mass movements on the planet. Around 70 major landslides have been identified around the Hawaiian Island archipelago, the largest having volumes in excess of 5000 km^3 and lengths of over 200 km (e.g. Moore *et al.* 1994). Such volcanic landslides are now proving to be widespread in the marine environment (Holcomb & Searle 1991; McGuire 1996; Masson *et al.* 2006). Around 5% of all tsunamis can be related to volcanic activity, and at least a fifth of these result from volcanic landslides entering the ocean (Smith & Shepherd 1996). Owing to an often greater vertical drop and to the high velocities attained, the tsunami-producing potential of a large body of debris entering the sea is much greater than that of a similar-sized submarine landslide, and even small subaerial volcanic landslides can generate locally highly destructive waves. In 1792, at Unzen volcano (Japan), for example, a landslide with a volume of only *ca* 0.33×10^9 m^3 triggered a tsunami that caused 14 500

Figure 4. Rounded cobbles and shell debris at elevations of up to 188 m.a.s.l. exposed in the Agaete Valley on Gran Canaria (Canary Islands) are interpreted (Pérez-Torrado *et al.* 2006) as having being emplaced by a giant tsunami arising from a pre-historic volcano lateral collapse in the archipelago. (Image courtesy of Simon Day.)

Figure 5. The western flank of the Cumbre Vieja volcano (La Palma, Canary Islands).

deaths. In 1888, several hundred deaths resulted from the lateral collapse of part of the Ritter Island volcano (Papua New Guinea), which generated tsunamis with proximal (less than 100 km) wave run-up heights of 12–15 m that remained 8 m high several hundred kilometres from source (Johnson 1987; Ward & Day 2003).



La Palma landslide tsunami

La Palma landslide tsunami

La Palma landslide tsunami

La Palma landslide tsunami

Figure 6. Time-slices from the Ward & Day (2001) La Palma tsunami model, showing the location of the wave train 30 min, 1 h, 3 h and 6 h after collapse. Positive numbers, wave crest heights (m); negative numbers, wave trough heights (m).

Tsunamis associated with *giant* collapses at oceanic-island volcanoes can, however, have run-up heights at least an order of magnitude greater. For example, a wave train associated with collapse of part of Mauna Loa (Hawaii), the Alika 2 Slide, around 120 000 years BP has been implicated in the emplacement of coral and other debris to an altitude of more than 400 m above contemporary sea level on the neighbouring volcano of Kohala (McMurtry *et al.* 2004). Giant waves generated by ancient collapses in the Hawaiian Islands may have been of Pacific-wide extent. Young & Bryant (1992) explained signs of catastrophic wave erosion up to 15 m above current sea level along the New South Wales coast of Australia, 14 000 km distant, in terms of impact by tsunamis associated with a major collapse in the Hawaiian archipelago around 1.05×10^5 years BP. These phenomena have also, however, been interpreted in terms of a tsunami generated by a marine impact.

Putative giant-tsunami deposits have been identified at increasing numbers of locations. On Gran Canaria in the Canary Islands, for example, deposits consisting of rounded cobbles and broken marine shells (figure 4) have been recognized at elevations of up to 188 m above present sea level (Pérez-Torrado *et al.* 2006), while similarly elevated comparable deposits occur on the neighbouring island of Fuerteventura (S. J. Day 2002, personal communication). Pérez-Torrado *et al.* (2006) propose that the Gran Canaria deposits were emplaced by tsunamis caused by flank failure of an island volcano in the archipelago, and tentatively suggest the Gűimar sector collapse (age$<8.3\times10^5$ years) on neighbouring Tenerife as a possible source. On the Rangiroa reef (French Polynesia), large coral boulders have been linked by Talandier & Bourrouilh-le-Jan (1988) with giant tsunamis formed by the early nineteenth century collapse of the Fatu Hiva volcano (Marquesas Islands, Southeast Pacific). Similarly, thousand-tonne boulders scattered along the northeast coast of the Bahamian island of Eleuthera, and associated geomorphological features (Hearty 1997; Hearty *et al.* 1998), may provide evidence of the impact of giant tsunamis from a major collapse event at the Canary Island of El Hierro that occurred around 120 kyr BP (Guillou *et al.* 1996).

Recently, considerable attention has been focused on the Cumbre Vieja volcano (La Palma, Canary Islands), and its tsunamigenic potential with respect to a future collapse of its unstable western flank (figure 5). The ability of past collapses in the Hawaiian and Canarian archipelagos to generate tsunamis in excess of 150 m high (McMurtry *et al.* 2004; Pérez-Torrado *et al.* 2006), along with evidence from the Ritter Island slide (Ward & Day 2003), argues for eventual flank failure of the Cumbre Vieja volcano to occur catastrophically. The Ritter Island collapse involved transport velocities of 45 m s^{-1} and perhaps as high as 80 m s^{-1} (Ward & Day 2003), and Ward & Day (2001) proposed an entry velocity as high as 100 m s^{-1} for a future major collapse of the Cumbre Vieja. There continues, however, to be major disagreement with respect to the nature of a future collapse of the Cumbre Vieja volcano and its potential to generate trans-oceanic tsunamis (e.g. Masson *et al.* 2006). Areas of dispute relate to the volume of material available for collapse, the slide velocity of the collapsing mass, the extent to which the collapse is retrogressive rather than a single slide and the ability of any resulting tsunamis to retain sufficient energy to be destructive in the far field.

In relation to the latter, Ward & Day (2001) have controversially modelled the consequences for a worst-case scenario (a 5×10^2 km^3 slide block moving at 100 m s^{-1}), predicting the formation of an initial dome of water 900 m in height that subsides to a series of waves hundreds of metres high. For collapse scenarios involving a range of slide blocks from 1.5 to 5×10^2 km^3, Ward & Day (2001) predict a wave train that transits the entire Atlantic Ocean (figure 6), with wave heights along the coast of the Americas ranging from 3–8 m (for a 1.5×10^2 km^3 slide) to 10–25 m (for a 5×10^2 km^3 slide). Mader (2001), however, proposes that wave heights along the east coast of the US, in response to a worst-case collapse would be less than 3 m and lower for smaller collapse volumes, while Pararas-Carayannis (2002) predicts that they will be as low as 1 m.

Opposing viewpoints centre on the efficiency with which large trans-oceanic tsunamis can be generated by what is essentially a point source (rather than the linear source typical of the biggest seismogenic tsunamis). Based upon calculations of Cumbre Vieja collapse tsunami potential using the SAGE hydrocode, Gisler *et al.* (2005) note that both the periods and wavelengths of waves produced are short

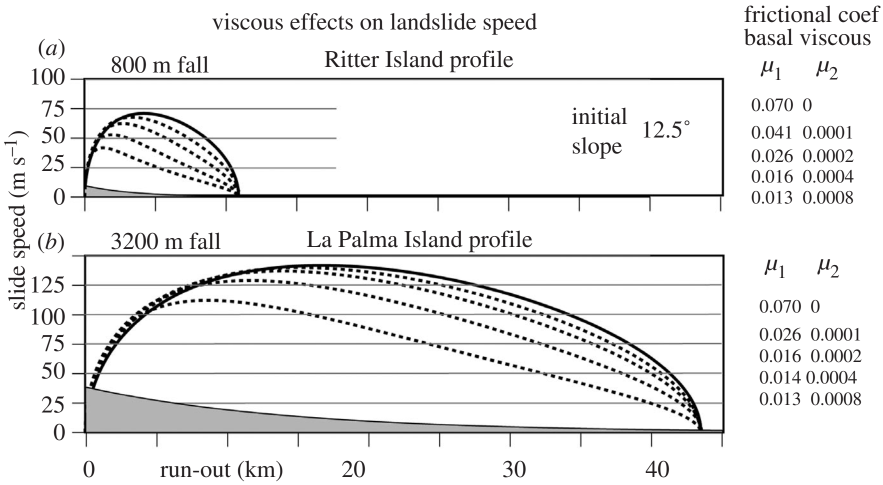


Figure 7. Velocity trajectories of (*a*) Ritter Island and (*b*) La Palma landslides with ($\mu_2 > 0$, dashed lines) and without ($\mu_2 = 0$, solid line) viscous dissipation. Uppermost dashed lines represent the most plausible μ_2 values. The grey area is the slope profile. Giant landslides, such as that threatened by the instability of the Cumbre Vieja's west flank, should run at speeds exceeding 100 m s^{-1}, even in the presence of viscous dissipation (from Ward & Day 2003).

compared to trans-oceanic tsunamis observed in the Indian and Pacific Oceans. While recognizing that a future lateral collapse could be expected to generate waves capable of being highly destructive within the Canary Island archipelago itself, and along the coasts of Morocco, Spain and Portugal, Gisler *et al.* (2005) suggest that the absence of long period–long wavelength waves will probably not permit the propagation of destructive waves to the east coast of North America. Focusing on the only major tsunamigenic collapse for which data are available, however, Ward & Day (2003) highlight the formation and importance of short (1–5 min) period tsunamis during the Ritter Island collapse, and their ability to transmit damaging and potentially lethal energy to distances of several hundred kilometres. A scaled-up Ritter Island collapse—in terms of fall height and other parameters (figure 7)—Ward & Day (2003) propose, would be capable of generating a trans-oceanic mega-tsunami (figure 7). Support for the persistence of short-period waves across oceanic distances comes from observations of tsunamis generated by nuclear tests at Bikini Atoll in the late 1950s and early 1960s. Van Dorn (1961) reports the measurement of 3–9 min waves (compared to 10 min in the Ward & Day Cumbre Vieja model) out to a distance of 2700 km. The wave decay rate described by Van Dorn is also in agreement with that proposed by Ward & Day (2001). Clearly, the potential for a future collapse of the Cumbre Vieja volcano to trigger a mega-tsunami will remain controversial. Until the situation is resolved, however, such a scenario should be given serious consideration.

10. Strategically located global geophysical events

There are few cities or regions on the planet whose destruction or serious disruption could be expected to have global consequences through deleterious effects on the world's economy and social fabric. New York and London qualify by dint of their roles as the planet's two principal financial centres. The low probability occurrence of a magnitude 7 earthquake affecting New York could cause damage, destruction and business interruption costing up to US$ 198 billion (NYCEM 2003). While not catastrophic, such an event could certainly be expected to disrupt the global economy for some time. The 'City' area of London is less exposed to large natural catastrophes, and due to its relative elevation, even a failure of the London flood defence system is unlikely to incur serious losses. Tokyo is far more susceptible to a catastrophic event that could bring about a failure of the global economic system. The cost of the 1999 Kocaeli earthquake amounted to 10% of Turkey's gross domestic product (GDP), while economic losses due to the 2003 Bam earthquake totalled around 12% of Iran's GDP. No earthquake, however, has resulted in consequences that are sufficiently wide-ranging to have a serious impact on the global economy. The conditions for such an event may, however, now exist in the Japanese capital. In 1923, Tokyo and the neighbouring city of Yokohama were virtually obliterated by the *Great Kanto Earthquake*—a magnitude 7.9 event that destroyed 360 000 buildings including 20 000 factories and 1500 schools. In Tokyo, 71% of the population lost their homes, with this figure rising to over 85% in Yokohama. Out of a population of 11.7 million, 104 000 were killed and a further 52 000 injured, with 3.2 million people left homeless. This was the worst natural disaster in the country's history, and is estimated to have cost around US$ 70 billion at today's prices. The event proved an unsustainable drain on the national economy and, together, the earthquake and the global economic crash that followed 6 years later triggered economic collapse, and is held as leading ultimately to militarism, expansionism and war.

The cities of Yokohama and Tokyo have now largely merged to form the Greater Tokyo metropolitan region; a gigantic agglomeration of 33 million people, some 26% of the nation's population, and the largest urban concentration on the planet. Despite improved building construction and a better understanding of the hazard, a threefold rise in the population of the region is predicted to see up to 60 000 lives lost in a repeat of the 1923 earthquake (Insurance Information Institute 2004). The economic cost of the event is forecasted to reach a staggering US$ 4.3 trillion (Insurance Information Institute 2004), up to 34 times the economic losses arising from Hurricane Katrina. After more than a decade of stagnation and the accumulation of a gigantic government debt one and a half times the country's GDP, there are serious concerns about the possibility of a future collapse of the Japanese financial system and resulting global economic turmoil. Prior to 1923, the last major earthquake to strike the capital region occurred in 1703, suggesting that such events may have recurrence intervals of a few centuries (see Stein *et al.* 2006). Such is the complexity of the tectonic situation in the Tokyo region, however, and the potential for interaction between different seismogenic faults, that making an accurate probabilistic forecast of the timing of the next Great Kanto Earthquake remains beyond current capabilities. Nevertheless, it would be reasonable to assume that it will arrive sometime within the next 100–500 years, heralding, depending upon the precise states of the Japanese and the world economies, a period of severe economic problems, perhaps on a global scale. With respect to smaller seismic events, Rikitake (1991) calculates a 40% 10-year probability of a magnitude 6 or greater earthquake and a 5% probability for a shock of magnitude 7 or greater.

The probability of an earthquake in the Tokyo region in the next 30 years, large enough to cause severe shaking (6 or more on the Japanese Meteorological Agency intensity scale), is between 35 and 45%. While unlikely to be comparable to the 1923 earthquake, such an event may cause economic losses of the order of US$ 1 trillion and seriously affect the global economy (Stein *et al.* 2006).

11. Addressing the global geophysical event threat

In different ways, both the Asian tsunami and Hurricane Katrina have drawn attention to the potential for single geophysical hazards to have consequences far beyond the reach of their direct physical effects. This has led to a perceptible change in outlook and calls for longer-term hazard assessment, monitoring and early warning that have led directly to planned tsunami warning systems in the Indian Ocean and North Atlantic basins. The idea that GGEs, such as volcanic super-eruptions and asteroid impacts, are events of the future that cannot affect us in the short term, however unlikely, is receding, and governments and international agencies are beginning to develop a longer-term perspective that looks to the twenty-second century and beyond. If nothing else, climate change is beginning to drive such a change of viewpoint, which is equally applicable and relevant to all GGEs.

Addressing the GGE threat in an effective manner necessitates a twofold approach that requires increased study and monitoring of potential threats linked to a programme of awareness-raising, education and contingency planning. While curiosity-driven research is both critical and thriving within the geophysical community, there has to be recognition that, in an increasingly hazardous and vulnerable world, the application of geophysical science to the management, mitigation and reduction of the natural hazard threat is a duty rather than an option. Alongside this, there has to be the will among those relevant funding bodies, national government departments, international agencies and non-governmental organizations, at the heart of the disaster risk reduction 'business', to accept that science has a critical role to play in dramatically reducing the threat of geophysical hazards. In particular, the geophysical community is ideally placed, through improved monitoring, modelling, forecasting and prediction, to enrich preparedness through identifying future threats and providing sufficient early warning of pending catastrophes. In order for this capability to be maximized, however, it has to be matched by key players in the disaster risk reduction community making a determined effort to reset the balance in favour of preparedness rather than response. Only through such a sea change in thinking can we even begin to make a dent in the number and scale of natural catastrophes arising from geophysical hazards in coming decades and beyond.

With respect to tackling GGEs and other major hazards capable of multi-state impact, there is now a concerted push to establish, at international level, a group with the remit to identify, evaluate and warn of future events with the potential to have serious consequences at the regional and global scale. In June 2005, the UK government's Natural Hazard Working Group (NHWG 2005), established by Prime Minister Tony Blair in the aftermath of the Asian tsunami, published its report: *The Role of Science in Physical Natural Hazard Assessment*. The report's prime recommendation was the establishment of an International Science Panel (ISP), designed to provide an accessible mechanism for the hazard and risk science community to advise decision-makers authoritatively on potential geophysical hazards capable of a high regional or global impact. As envisaged by the NHWG, the Panel would provide an apparatus within which individual scientists and research groups could pool their knowledge and challenge one another, with respect to identifying and validating future threats. Alongside this, the Panel would provide a means for highlighting serious gaps in knowledge and address the application of science to managing and mitigating major geophysical threats and reducing vulnerability and exposure to them. Following support for the initiative at the G8 conference at Gleneagles (Scotland) in July 2005, UK government departments are now working with the UN International Strategy for Disaster Reduction and others at the UN to ensure that the ISP concept becomes a working reality in some form. Clearly, if we are to avoid a repeat of the appalling destruction and carnage of 26th December 2004, this is an initiative that neither the geophysical community nor those organizations dedicated to disaster risk reduction can afford to allow to fail.

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