

REVIEW

Potential for a hazardous geospheric response to projected future climate changes

BY B. MCGUIRE*

*Aon Benfield UCL Hazard Research Centre, Department of Earth Sciences,
University College London, Gower Street, London WC1E 6BT, UK*

Periods of exceptional climate change in Earth history are associated with a dynamic response from the geosphere, involving enhanced levels of potentially hazardous geological and geomorphological activity. The response is expressed through the adjustment, modulation or triggering of a broad range of surface and crustal phenomena, including volcanic and seismic activity, submarine and subaerial landslides, tsunamis and landslide ‘splash’ waves, glacial outburst and rock-dam failure floods, debris flows and gas-hydrate destabilization. In relation to anthropogenic climate change, modelling studies and projection of current trends point towards increased risk in relation to a spectrum of geological and geomorphological hazards in a warmer world, while observations suggest that the ongoing rise in global average temperatures may already be eliciting a hazardous response from the geosphere. Here, the potential influences of anthropogenic warming are reviewed in relation to an array of geological and geomorphological hazards across a range of environmental settings. A programme of focused research is advocated in order to: (i) understand better those mechanisms by which contemporary climate change may drive hazardous geological and geomorphological activity; (ii) delineate those parts of the world that are most susceptible; and (iii) provide a more robust appreciation of potential impacts for society and infrastructure.

Keywords: climate change; geosphere; geological hazard; geomorphological hazard; ocean loading; ice-mass loss

1. Introduction

Concern over anthropogenic climate change driving hazardous geological and geomorphological activity is justified on the basis of four lines of evidence: (i) periods of exceptional climate change in Earth history are associated with a dynamic response from the geosphere; (ii) small changes in environmental conditions provide a means whereby physical phenomena involving the atmosphere and hydrosphere can elicit a reaction from the Earth’s crust and sometimes at deeper

*w.mcguire@ucl.ac.uk

One contribution of 15 to a Theme Issue ‘Climate forcing of geological and geomorphological hazards’.

levels; (iii) modelling studies and projection of current trends point towards increased risk in relation to a range of geological and geomorphological hazards in a warmer world; and (iv) observations suggest that the ongoing rise in global average temperatures may already be eliciting a hazardous response from the geosphere.

A link between past climate change and enhanced levels of potentially hazardous geological and geomorphological activity is well established, with supporting evidence coming mostly, though not exclusively, from the period following the end of the last glacial maximum (LGM) around 20 ka BP. During the latest Pleistocene and the Holocene, the atmosphere and hydrosphere underwent dramatic transformations. Rapid planetary warming promoted a major reorganization of the global water budget as continental ice sheets melted to replenish depleted ocean volumes, resulting in a cumulative sea-level rise of *ca* 130 m. Contemporaneously, atmospheric circulation patterns changed to accommodate broadly warmer, wetter conditions, leading to modification of major wind trends and a rearrangement of climatic zones.

The nature of the geospheric response to transitions from glacial to interglacial periods provides the context for evaluating the potential of current greenhouse gas (GHG) related warming to influence the frequency and incidence of geological and geomorphological hazards. Critically, however, differences in the time scale, degree and rate of contemporary environmental change may result in a different hazard response. The key question, therefore, is: to what extent does the post-glacial period provide an analogue for climate-change-driven hazards in the twenty-first century and beyond?

2. Climate change as a driver of geological and geomorphological hazards at glacial–interglacial transitions

At the broadest of scales, modification of the global pattern of stress and strain, due to a major redistribution of planetary water, may influence geological and geomorphological activity at times of glacial–interglacial transition (Matthews 1969; Podolskiy 2008). As noted by Liggins *et al.* (2010), however, a more targeted geospheric response to planetary warming and hydrological adjustment during these times is associated with ice-mass loss, rapid sea-level rise and greater availability of liquid water, in the form either of ice melt or of increased precipitation levels. These environmental transformations in turn drive load-pressure changes and increases in pore-water pressure that, together, act to promote hazardous geological and geomorphological activity. Notably, variations in ice and water load have been linked to fault rupture (Hampel *et al.* 2007, 2010), magma production and eruption (McNutt & Beavan 1987; McNutt 1999; Pagli & Sigmundsson 2008; Sigmundsson *et al.* 2010) and submarine mass movements (Lee 2009; Tappin 2010). Elevated pore-water pressures are frequently implicated in the formation of subaerial and marine landslides (Pratt *et al.* 2002; Tappin 2010).

The geospheric response to such changes in environmental conditions at times of glacial–interglacial transition is expressed through the adjustment, modulation or triggering of a wide range of surface and crustal phenomena, including volcanic (e.g. Chappel 1975; Kennett & Thunell 1975; Rampino *et al.* 1979;

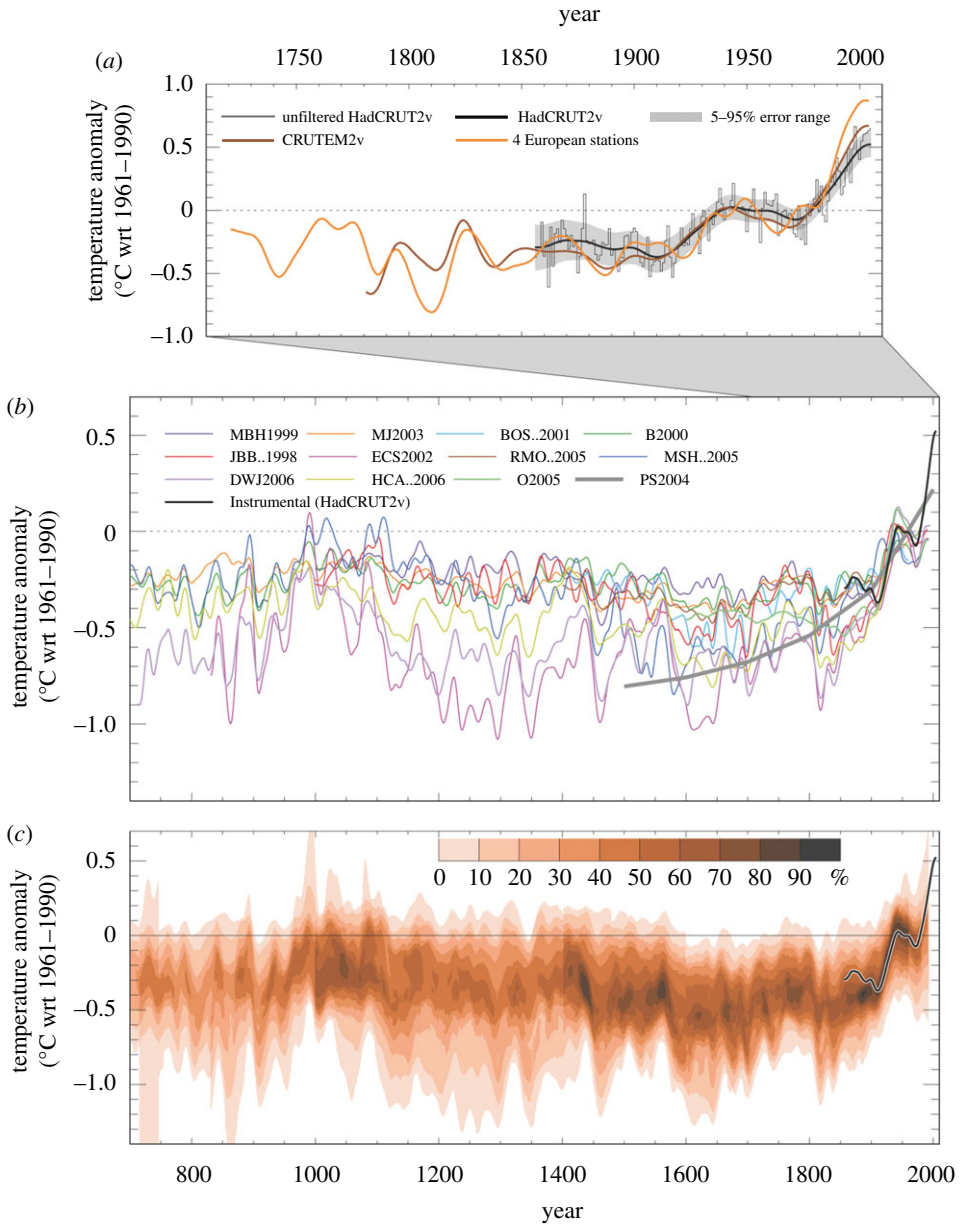


Figure 1. Records of Northern Hemisphere temperature variation during the last 1300 years: (a) annual mean instrumental temperature records; (b) reconstructions using multiple climate proxy records (see original source for details); and (c) overlap of the published multi-decadal time-scale uncertainty ranges of temperature reconstructions. The HadCRUT2v instrumental temperature record is shown in black. All series have been smoothed with a Gaussian-weighted filter to remove fluctuations on time scales less than 30 years; smoothed values are obtained up to both ends of each record by extending the records with the mean of the adjacent existing values. All temperatures represent anomalies (°C) from the 1961 to 1990 mean. (Adapted from fig. 6.10 in IPCC (2007). Copyright © IPCC.)

Hall 1982; Wallman *et al.* 1988; Nakada & Yokose 1992; Sigvaldason *et al.* 1992; Jull & McKenzie 1996; McGuire *et al.* 1997; Zielinski *et al.* 1997; Glazner *et al.* 1999; MacLennan *et al.* 2002; Bay *et al.* 2004; Jellinek *et al.* 2004; Nowell *et al.* 2006; Licciardi *et al.* 2007; Bigg *et al.* 2008; Carrivick *et al.* 2009a; Huybers & Langmuir 2009) and seismic (e.g. Anderson 1974; Davenport *et al.* 1989; Costain & Bollinger 1996; Wu *et al.* 1999; Wu & Johnston 2000; Hetzel & Hampel 2005) activity, marine (e.g. Maslin *et al.* 1998; Day *et al.* 1999, 2000; Masson *et al.* 2002; Keating & McGuire 2004; Maslin *et al.* 2004; McMurtry *et al.* 2004; Vanneste *et al.* 2006; Quidelleur *et al.* 2008; Lee 2009; Tappin 2010) and subaerial (Lateltin *et al.* 1997; Friele & Clague 2004; Capra 2006) landslides, tsunamis (McMurtry *et al.* 2004; Lee 2009), landslide 'splash' waves (Hermanns *et al.* 2004), glacial outburst (Alho *et al.* 2005) and rock-dam failure (Hermanns *et al.* 2004) floods, debris flows (Keefer *et al.* 2000) and gas-hydrate destabilization (e.g. Henriot & Mienert 1998; Maslin *et al.* 2004; Beget & Addison 2007; Grozic 2009).

The degree to which comparable responses to projected future climate changes could modify the risk of geological and geomorphological hazards is likely to be dependent in significant measure on the scale and rate of future climate change. The measure of changes in key environmental conditions in post-glacial times was considerable, with the rapid loss of continental ice sheets following the LGM leading to cumulative load-pressure reductions on the crust of a few tens of megapascals, and sea levels in excess of 100 m higher increasing the total load on the crust by *ca* 1 MPa. Rates of change were also dramatic, with annual vertical mass wastage of between 10 and 50 m (corresponding to a load reduction of 10–50 kPa) reported for the Wisconsin Laurentide ice sheet (Andrews 1973). The rate of global eustatic sea-level rise may have approached 5 m per century at times, with annual rates of more than 45 mm (Blanchon & Shaw 1995), resulting in an annual load-pressure increase on the crust of *ca* 1 kPa. Given the scale of absolute changes and the very high rates involved, it is unsurprising that imposition of such stresses within the crustal domain elicited a significant geological and geomorphological response. While the post-LGM climate of the latest Pleistocene and the Holocene was characterized by considerable variability (Mayewski *et al.* 2004), the transition from 'ice-world' to 'water-world' broadly altered the moisture balance so as to favour a far greater incidence of warm and wet conditions, for example, during the African Humid Period from *ca* 14.8 to 5.5 ka BP (Hély *et al.* 2009) and during the Early Holocene across much of the Mediterranean (Frisia *et al.* 2006). Higher levels of precipitation raised the potential for higher pore-water pressures in unstable volumes of rock and debris, promoting landslide formation. Pratt *et al.* (2002), for example, speculate that enhanced monsoon rainfall during the Early Holocene raised pore-water pressures in the Nepal Himalaya, resulting in an increase in landslide frequency. Similarly, Capra (2006) invokes more humid Holocene conditions to explain an apparent increase in the incidence of lateral collapse of volcanic edifices. In relation to the formation of submarine landslides in the post-glacial period, a range of potential environmental triggers are proposed, most notably elevated levels of seismicity associated with isostatic rebound of previously ice-covered crust, or to ocean loading due to rapid sea-level rise, but also to elevated sediment pore pressures and gas-hydrate destabilization (see Lee (2009) for more comprehensive discussion of these factors).

3. Projected future climate changes and the potential for a geospheric response

Since the LGM, *ca* 20 ka BP, global average temperatures have risen by around 6°C, with a rise of close to 0.8°C occurring in the last 100 years (figure 1). Without a major change in energy policy, GHG emissions are projected to rise substantially, increasing the global mean temperature by between 1.6 and 6.9°C relative to pre-industrial times, driving long-term rises in temperature and global sea level and possible changes to the Atlantic meridional overturning circulation (MOC) (IPCC 2007; figure 2). As noted by Liggins *et al.* (2010), physical inertia in the climate system ensures that the full effect of past anthropogenic forcing remains to be realized. Considering that global GHG emissions are still on an upward trend, and with no binding agreement in place to reduce this, it is highly probable that warming will result in regional temperature rises of at least 2°C above the pre-industrial period. Under the highest IPCC SRES (*IPCC special report on emissions scenarios*; Nakicenovic *et al.* 2000) emissions scenario (A1F1), Betts *et al.* (submitted) show that global average temperatures are likely to reach 4°C relative to pre-industrial times, by the 2070s, and perhaps as early as 2060. Under the lowest of the main emissions scenarios (B1), the central estimate of warming is projected to be 2.3°C relative to the pre-industrial period. These projections indicate that the current episode of GHG-driven warming is exceptional. As observed in the IPCC's fourth assessment report (AR4; IPCC 2007), if temperatures rise *ca* 5°C by 2100, the Earth will have experienced approximately the same amount of warming in a few centuries as it did over several thousand years following the LGM. This rate of warming is not matched by any comparable global average temperature rise in the last 50 million years. Furthermore, high latitudes, where most residual ice now resides, are expected to warm even more rapidly. Christensen *et al.* (2007), for example, propose that, under the A1B scenario, the Arctic (north of 60° N) could warm by between 2.8 and 7.8°C by 2080–2099 (relative to 1980–1999). 'High-end' projections under the A2 scenario suggest that surface temperatures across much of the Arctic could increase by 15°C by the 2090s (Sanderson *et al.* submitted).

Global temperature rises are driving increases in ocean volume due to thermal expansion of sea water and via melting of glaciers, ice caps and the Greenland and West Antarctic ice sheets. Dependent upon the scenario, annual thermosteric sea-level rise by 2100 could lie between 1.9 ± 1.0 mm (B1 scenario) and 3.8 ± 1.3 mm (A2) (Meehl *et al.* 2007). Total global mean sea-level rise by the end of the century is projected in the IPCC AR4 (IPCC 2007) to be between 0.18 and 0.59 m. Even the high end of these projections may, however, be an underestimate. Rahmstorf (2007), for example, argues for a rise of 0.5–1.4 m by the end of the century, while Pfeffer *et al.* (2008) estimate an upper bound of 2 m by 2100.

Projected changes in other climate quantities are also relevant in relation to influencing potentially hazardous crustal and surface processes, most notably variations in patterns of precipitation. Under the A1B scenario, for example, the Arctic (north of 60° N) is projected to see a 28 per cent increase in precipitation by 2080–2099 relative to 1980–1999 (Christensen *et al.* 2007), and a similar rise is expected for Alaska and Kamchatka (Liggins *et al.* 2010). Ocean warming may also be important, and, while this is projected to progress more slowly than over

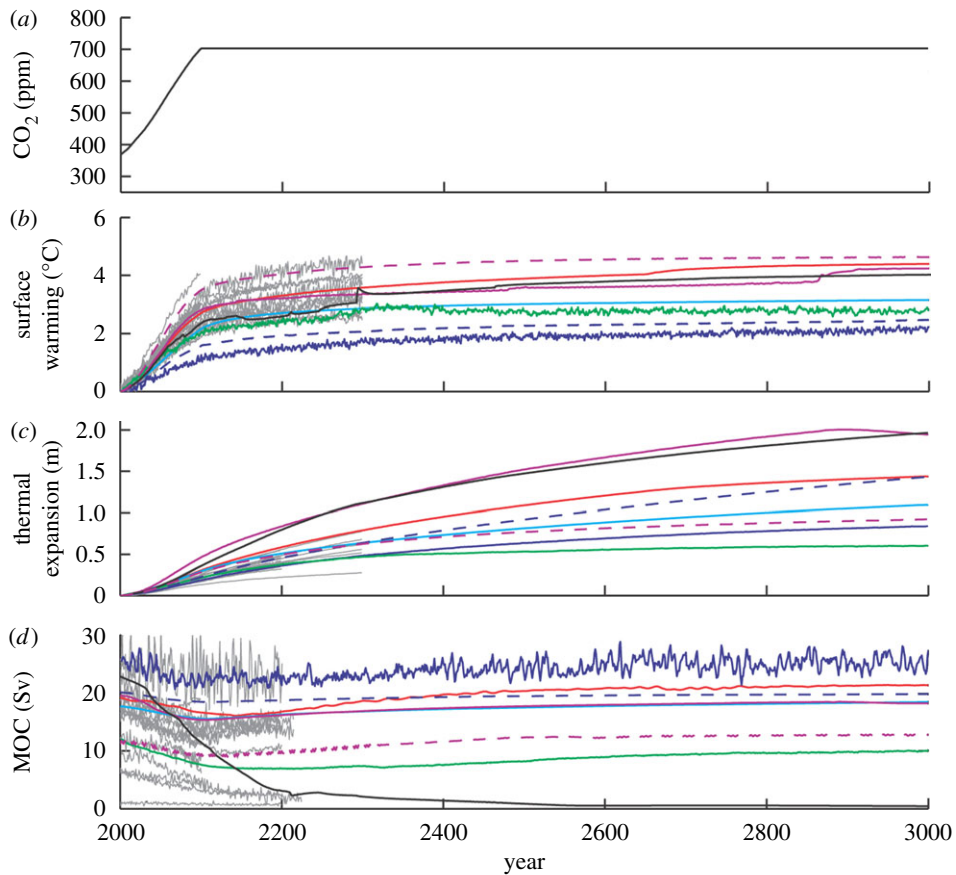


Figure 2. Projected changes in (a) atmospheric CO_2 , (b) global mean surface warming, (c) sea-level rise from thermal expansion, and (d) Atlantic meridional overturning circulation (MOC, sverdrups) calculated by eight Earth system models of intermediate complexity (EMICs) for the SRES A1B scenario and stable radiative forcing after 2100, showing long-term commitment after stabilization. Coloured lines are results from EMICs, grey lines indicate atmosphere–ocean general circulation model (AOGCM) results where available for comparison. Anomalies in (b,c) are given relative to the year 2000. Vertical bars indicate ± 2 s.d. uncertainties due to ocean parameter perturbations in the C-GOLDSTEIN model. The MOC shuts down in the BERN2.5CC model, leading to an additional contribution to sea-level rise. Individual EMICs treat the effect from non- CO_2 GHGs and the direct and indirect aerosol effects on radiative forcing differently. Despite similar atmospheric CO_2 concentrations, radiative forcing among EMICs can thus differ within the uncertainty ranges currently available for present-day radiative forcing. Red line, UVIC; dark blue line, LOVECLIM; light blue line, C-GOLDSTEIN; green line, MIT-IGSM2.3; dark blue dashed line, MOBIDIC; pink line, CLIMBER-2; black line, BERN2.5CC; pink dashed line, CLIMBER-3 α . (Adapted from fig. 10.34 in IPCC (2007). Copyright © IPCC.)

land masses (Meehl *et al.* 2007), it is expected to be greatest at high latitudes, where it may play a role in accelerating ice wastage and in contributing towards gas-hydrate dissociation.

Projected rising temperatures and sea levels, and changes in precipitation, are capable of initiating load changes and elevated pore-water pressures that exceed levels that have been shown to drive a range of geological and geomorphological

processes that have hazard potential. Small ice masses are already experiencing serious wastage, with surging and thinning of some glaciers resulting in vertical mass reduction of tens to hundreds of metres (Doser *et al.* 2007), leading to load-pressure declines on basement rocks of 0.5 MPa or more (Sauber *et al.* 2000). Comparable load-pressure falls may be expected in relation to the Greenland and West Antarctic ice sheets if increased melting accelerates ice loss and glaciers surge and thin. The projected 0.18–0.59 m rise in sea level by the end of the century (IPCC 2007) would result in an increased load on the crust of 1.8–5.9 kPa. For a rise of up to 1.4 m (Rahmstorf 2007), the load change rises to 14 kPa, and to 20 kPa for the upper-bound 2 m rise of Pfeffer *et al.* (2008). Recently (1993–2003), annual sea-level rise has been of the order of 2.4–3.8 mm yr⁻¹ (IPCC 2007), which translates broadly to an increased load pressure of 0.1 kPa every 3 years.

While the load-pressure changes associated with GHG-driven ice wastage and sea-level rise are generally small, in terms of both absolute values and rates, they may be sufficient to trigger a geospheric response. Mounting evidence makes a convincing case for the modulation or triggering of seismic, volcanic and landslide activity as a consequence of small changes in environmental parameters such as solid Earth and ocean tides and atmospheric temperature and pressure, as well as in response to specific geophysical events such as typhoons or torrential precipitation (table 1).

Based upon observations of seismicity from southeast Germany, Hainzl *et al.* (2006) demonstrate that the crust can sometimes be so close to failure that even tiny (less than 1 kPa) pore-pressure variations associated with precipitation can trigger earthquakes in the top few kilometres. Christiansen *et al.* (2007) propose that modulation of seismicity on a creeping section of the San Andreas Fault in the vicinity of Parkfield is linked to the hydrological cycle. The authors suggest that fracturing of critically stressed rocks occurs as a consequence of either pore-pressure diffusion or crustal loading/unloading, and note that hydrologically induced stress perturbations of *ca* 2 kPa may be sufficient to trigger earthquakes on the fault. In volcanic settings, Mastin (1994) relates the violent venting of volcanic gases at Mount St Helens between 1989 and 1991 to slope instability or accelerated growth of cooling fractures within the lava dome following rainstorms, while Matthews *et al.* (2002) link episodes of intense tropical rainfall with collapses of the Soufriere Hills lava dome on Montserrat (Caribbean).

Liu *et al.* (2009) show that slow earthquakes in eastern Taiwan are triggered by stress changes of *ca* 2 kPa on faults at depth, associated with atmospheric pressure falls caused by passing tropical cyclones. Rubinstein *et al.* (2008) have been able to correlate episodes of slow fault slip and accompanying seismic tremor at subduction zones in Cascadia (Pacific North West) and Japan with the rise and fall of ocean tides, which involve peak-to-peak load-pressure changes (for Cascadia) of 15 kPa. Heki (2003) demonstrates that snow load seasonally influences the seismicity of Japan through increasing compression on active faults and reducing the Coulomb failure stress by a few kilopascals. Schultz *et al.* (2009) show that diurnal tidal variations in atmospheric pressure amounting to less than 1 kPa modulate daily slip on the Slumgullion landslide in southwest Colorado. For volcanoes, Earth tides (Johnston & Mauk 1972; Hamilton 1973; Sparks 1981) and other changing external factors, such as barometric pressure (Neuberg 2000) or ocean loading (McNutt & Beavan 1987; McNutt 1999), have been proposed as having roles in forcing or modulating activity. McNutt & Beavan (1987) and

Table 1. Examples of environmental drivers of seismicity, landslide slip and eruptive activity described in the literature, together with associated driving pressures. Pressure changes related to twentieth century glacier ice-mass loss in Alaska and to future sea-level rise scenarios are included for comparison.

process	environmental driver	driving pressures	references
<i>contemporary observations</i>			
seismicity (SE Germany)	precipitation	<1 kPa	Hainzl <i>et al.</i> (2006)
seismicity (San Andreas Fault, California)	precipitation	ca 2 kPa	Christiansen <i>et al.</i> (2007)
seismic tremor/slow fault slip (Japan/Cascadia subduction zone)	ocean loading	15 kPa	Rubinstein <i>et al.</i> (2008)
seismicity (Japan)	snow loading	'a few kPa'	Heki (2003)
daily slip (Slumgullion landslide, Colorado)	atmospheric pressure variation	<1 kPa	Schultz <i>et al.</i> (2009)
eruptive activity (Pavlof, Alaska)	ocean loading	2 kPa	McNutt & Beavan (1987) and McNutt (1999)
seismicity	snow unloading and ground-water recharge	>5 kPa	Christiansen <i>et al.</i> (2005)
seismicity (Juan de Fuca Ridge, NE Pacific)	ocean loading	30–40 kPa	Wilcock (2001)
seismicity (East Pacific Rise)	ocean unloading	1–2 kPa	Guillas <i>et al.</i> (2010)
<i>climate-change impacts and projections</i>			
glacier ice-mass loss (Alaska)	ice unloading	up to 2 MPa	Sauber & Molnia (2004)
current (1993–2003) rate of sea-level rise	ocean loading	0.1 kPa every 3 years	IPCC (2007)
global average sea-level rise (by 2100)	ocean loading	1.8–5.9 kPa	IPCC (2007)
global average sea-level rise (by 2100)	ocean loading	up to 14 kPa	Rahmstorf (2007)

McNutt (1999), for example, suggest that eruptions of the Pavlof (Alaska) volcano, from the early 1970s to the late 1990s, were modulated by ocean loading involving yearly, non-tidal, variations in local sea level as small as 20 cm, which translates to a load-pressure change on the crust of 2 kPa. On a geographically broader scale, Bettinelli *et al.* (2008) explain seasonal variations in the seismicity of the Himalayas in terms of changes in surface hydrology, while Christiansen *et al.* (2005) link shallow (less than 3 km) seasonal seismicity at large calderas

and strato-volcanoes across the western USA with stress changes of greater than 5 kPa associated with snow unloading and ground-water recharge. Guillas *et al.* (2010) argue for reduced sea level in the eastern Pacific prior to the development of El Niño conditions, and approximating to a 1–2 kPa sea-bed load reduction, triggering increased levels of seismicity on the East Pacific Rise. At the global level, Mason *et al.* (2004) present evidence from the last 300 years in support of a seasonal signal in volcanic activity. This they attribute to fluctuations across a range of environmental conditions associated with the deformation of the Earth in response to the annual hydrological cycle, including reduced sea levels, millimetre-scale motion of the Earth's crust and falls in regional atmospheric pressure. While far from established, Podolskiy (2008) makes a case for an increase in global seismicity in recent decades, citing climate change as one potential driver.

4. Climate forcing of hazards in the geosphere

In light of the above, the potential is addressed for enhanced responses to changing environmental conditions, so as to increase the risk of geological and geomorphological hazards in a GHG-warmed world. In the context of rising atmospheric and ocean temperatures, ice-mass wastage and changing patterns of precipitation, possible implications are examined for high-latitude regions, ocean basins and margins, mountainous terrain and volcanic landscapes (table 2 and figure 3).

(a) *High-latitude regions*

The effects of anthropogenic climate change will be greater and more rapidly apparent at high latitudes. The potential for triggering geological and geomorphological hazards is also elevated, most notably as ice mass is lost from the great ice sheets, smaller ice caps and individual glaciers and ice fields. In Greenland and Antarctica, isostatic rebound as ice mass is reduced may result in increased seismicity (Turpeinen *et al.* 2008; Hampel *et al.* 2010), which may in turn trigger submarine landslides that could be tsunamigenic (Tappin 2010). In Iceland, Kamchatka and Alaska, melting of ice in volcanically and tectonically active terrains may herald a rise in the frequency of volcanic activity (Pagli & Sigmundsson 2008; Sigmundsson *et al.* 2010) and earthquakes (Sauber & Molnia 2004; Sauber & Ruppert 2008).

During post-glacial times, the melting of major continental ice sheets, such as the Laurentian and Fennoscandian, triggered intense seismic activity associated with isostatic rebound of the crust (e.g. Wu 1999; Wu *et al.* 1999; Muir-Wood 2000). For a 1 km ice load, the rebound may have amounted to hundreds of metres, with associated stresses totalling several megapascals, comparable with plate-driving stresses (Stewart *et al.* 2000). Ice thicknesses at Greenland and Antarctica currently exceed 3 km, providing potential for an ultimate rebound of more than 1 km should all the ice melt. While this is an extreme scenario, smaller-scale ice loss may also trigger a potentially hazardous seismic response as high-latitude temperatures climb. Turpeinen *et al.* (2008) use finite-element modelling in support of the idea (e.g. Johnston 1987) that current low levels of

Table 2. Potential geological and geomorphological hazards in the context of projected future climate changes. Columns show responsible mechanisms and relationship to climate change, relevant climate drivers and most susceptible environmental settings. Appropriate references from this issue are also indicated.

potential hazard	mechanism/potential relationship with climate change	relevant climate drivers	environmental settings	references (in this issue)
subaerial landslides and debris flows	permafrost thaw; pore-water pressurization; intense rainfall destabilizing regolith	temperature rise; ice-mass loss; intense precipitation	mountainous terrain; volcanic landscapes	Deeming <i>et al.</i> (2010), Hugel <i>et al.</i> (2010), Keiler <i>et al.</i> (2010) and Tuffen (2010)
glacial outburst floods (GLOFs)	glacier retreat; accumulation of meltwater in pro-glacial lakes	temperature rise; ice-mass loss	high latitudes; mountainous terrain; glaciated volcanic landscapes	Keiler <i>et al.</i> (2010) and Tuffen (2010)
earthquakes	ice-sheet and glacier wastage; ocean island and ocean margin loading due to sea-level rise	temperature rise; ice-mass loss; ocean volume increase	high latitudes; glaciated terrain at mid-to-low latitudes; ocean basins and margins	Hampel <i>et al.</i> (2010) and Guillas <i>et al.</i> (2010)
volcanic activity	unloading due to ice-sheet and glacier wastage; loading due to sea-level rise; pore-water pressurization; intense rainfall destabilizing regolith	temperature rise; ice-mass loss; intense precipitation; ocean volume increase	volcanic landscapes at all latitudes	Deeming <i>et al.</i> (2010), Sigmundsson <i>et al.</i> (2010) and Tuffen <i>et al.</i> (2010)
tsunamis	submarine and subaerial slope failures and volcano lateral collapses; gas-hydrate breakdown; ocean load-related earthquakes; ice quakes	ocean temperature rise; ocean volume increase; intense precipitation	ocean basins and margins	Day & Maslin (2010), Maslin <i>et al.</i> (2010), Dunkley Jones <i>et al.</i> (2010) and Tappin (2010)

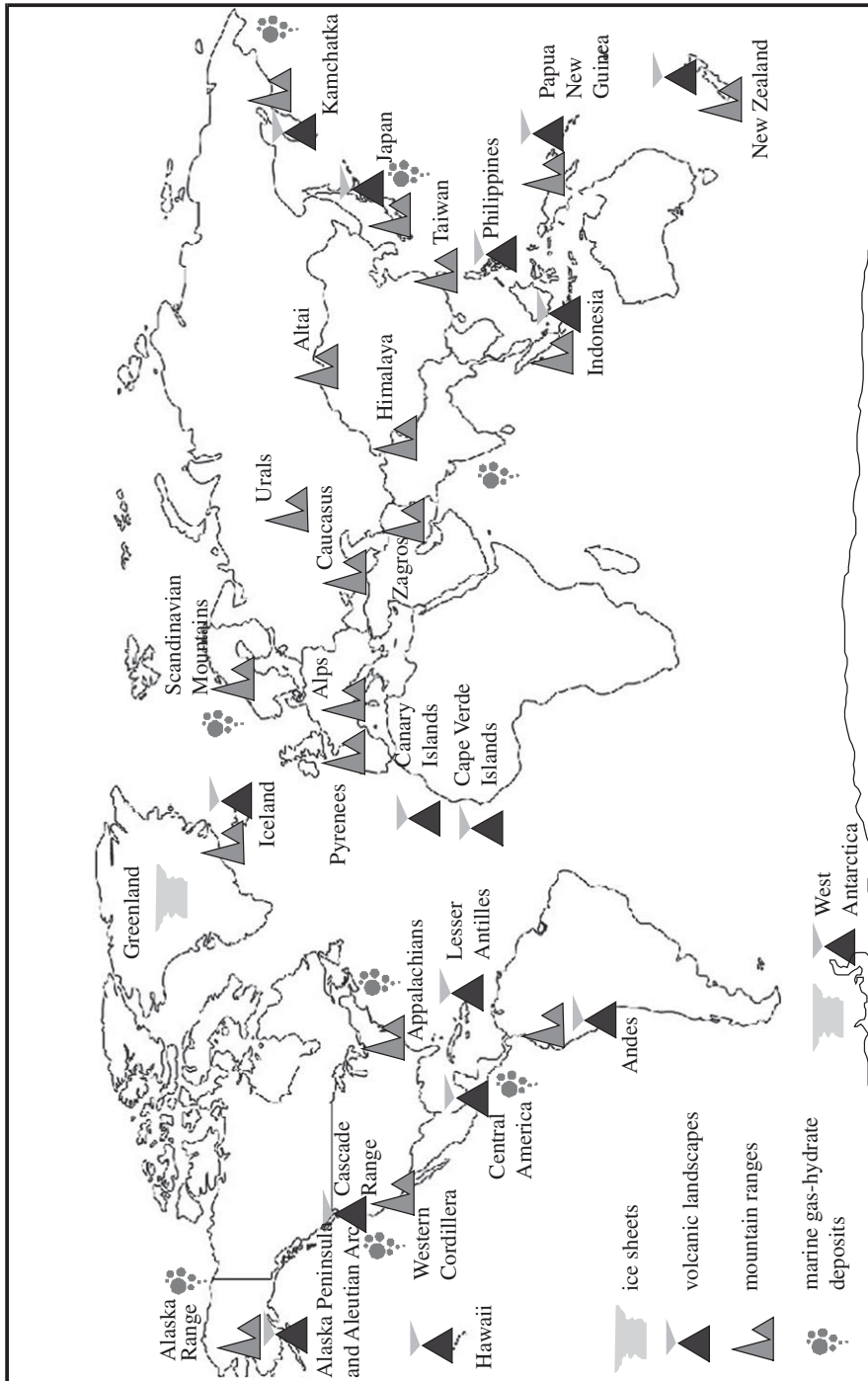


Figure 3. Notable high-latitude ice sheets, areas of mountainous terrain, active volcanoes and gas-hydrate concentrations susceptible to the impacts of rising temperatures, ice-mass loss, increasing ocean volume and higher levels of precipitation due to anthropogenic climate change. Consequent potential geological and geomorphological hazards are summarized in table 2.

seismicity in regions such as Greenland and Antarctica are a consequence of ice-sheet load, and speculate that future deglaciation of these regions may result in a pronounced increase in seismicity.

Song (2009) highlights an additional potential threat from ‘ice quakes’ (Ekstrom *et al.* 2003) associated with a future break-up of the Greenland and West Antarctic ice sheets. The author calculates that impulse energies from glacial earthquakes in both Greenland and West Antarctica are capable of generating significantly more powerful tsunamis than submarine earthquakes of similar magnitude, and notes that this may pose a threat to high-latitude regions such as Chile, New Zealand and Newfoundland (Canada).

Maslin *et al.* (2010) note that isostatic rebound of Greenland and Antarctica may also involve adjacent continental slope, thereby reducing pressure on any gas hydrates contained in slope sediments, raising the chances of hydrate breakdown and the related threat of tsunamigenic submarine landslides. Notwithstanding a gas-hydrate trigger, increased numbers of earthquakes may themselves be capable of triggering landsliding of piles of glacial sediment accumulated around the margins of the Greenland and Antarctic land masses. Such a mechanism has been shown to be important in triggering major submarine landslides in the post-glacial period, the best known of which is the Storegga Slide, formed off the coast of Norway 8.1 ± 0.25 ka BP (Lee 2009; Tappin 2010). With a volume of between 2500 and 3500 km³, the Storegga Slide is one of the world’s largest landslides, and is widely regarded to have been triggered by a strong earthquake associated with the isostatic rebound of Fennoscandia (Bryn *et al.* 2005). From the perspective of future hazard potential, it is noteworthy that the Storegga event generated a major tsunami (Tappin 2010), with tsunami deposits identified at heights above estimated contemporary sea level of 10–12 m on the Norwegian coast, more than 20 m in the Shetland Islands and 3–6 m on the coast of northeast Scotland (Bondevik *et al.* 2005). A range of mechanisms capable of being driven by anthropogenic climate change are presented by Tappin (2010) as having the potential to contribute to the formation of submarine mass failures, including earthquakes and cyclic loading due to storms or tides. Pore-fluid pressurization and gas-hydrate instability are held up by the author as possible contributors to slope destabilization, but are thought unlikely to play a triggering role in the failure process.

Projected temperature rises for high latitudes will affect smaller ice caps, ice fields and glaciers more rapidly than the major ice sheets. Of these, the Vatnajökull ice cap (area *ca* 8000 km²) (figure 4) in Iceland presents the greatest threat in relation to the resultant triggering of a potentially hazardous geospheric response. As reported in Pagli *et al.* (2007), mass-balance measurements show that the ice cap is thinning at a current rate of *ca* 0.5 m a year, and has lost *ca* 435 km³ between 1890 and 2003—about 10 per cent of the total volume. In post-glacial times, the reduction in vertical load associated with an annual ice thinning rate of *ca* 2 m, across a much larger ice cap (180 km diameter compared with 50 km today) (Pagli *et al.* 2007), was instrumental in triggering a significant increase in the frequency of volcanic eruptions. Furthermore, Jull & McKenzie (1996) showed that removal of the countrywide ice load reduced pressure on the underlying mantle to such a degree that melt production jumped by a factor of 30. The smaller size of the current Vatnajökull ice cap, and slower thinning rate, supports a more measured reaction from the crust and mantle to contemporary warming.

Nevertheless, Pagli & Sigmundsson (2008) predict, on the basis of finite-element modelling, that the reduced ice load will result in an additional 1.4 km^3 of melt being produced in the underlying mantle every century, comparable to an eruption equivalent in size to the 1996 Gjalp eruption beneath Vatnajökull, every 30 years. The authors also speculate that stress changes in the crust in response to ice-mass loss may already be contributing towards elevated levels of seismicity with 'unusual' focal mechanisms in the northwest of the region. From a future seismic risk viewpoint, it is worth observing that Hampel *et al.* (2007) demonstrate a clear seismic response to deglaciation of the $16\,500 \text{ km}^2$ area Yellowstone ice cap (northwest USA), including significantly elevated slip rates on the Teton Fault.

While the direct effects of increased levels of volcanic eruptions in Iceland may impinge upon relatively small populations, large events that are explosive or release significant volumes of sulphur gas may have far wider effects. The Laki (Lakagigar) eruption in 1783, for example, generated a tropospheric sulphurous haze that spread southeastwards over Europe. This resulted in extremely poor air quality and anomalously high temperatures during the summer months, and dramatically reduced winter temperatures, and led to significant excess deaths in the UK and continental Europe (e.g. Grattan *et al.* 2005). Furthermore, the 1783 eruption lasted for six months; a similar event today would have the potential to cause major disruption to the North Polar air transport routes.

Elevated levels of either volcanic or seismic activity on Iceland may also result in the triggering of secondary hazards, most notably glacial floods (Jökulhlaups) through rapid melting of ice during subglacial eruptions (e.g. Alho *et al.* 2005) and landslides or snow avalanches caused by ground accelerations during earthquakes (Saemundsson *et al.* 2003). Jökulhlaups currently pose a periodic threat to settlements and the main coast road immediately south of Vatnajökull, and these could reasonably be expected to increase should the incidence of volcanic activity rise as predicted. Jökulhlaups also occur in Greenland, where they may become more common as the climate warms and present a threat to communities and infrastructure (Mernild *et al.* 2008).

Outside of Iceland, at high latitudes, ice-mass wastage is expected to promote a comparable response, leading to increased levels of seismic and volcanic activity. Glacier mass fluctuations in south central Alaska have been charged with modulating the recent seismic record, and even implicated in the triggering of the 1979 magnitude 7.2 St Elias earthquake (Sauber *et al.* 2000; Sauber & Molnia 2004; Sauber & Ruppert 2008). Rapid ice-mass loss at the many glaciated volcanoes in Alaska and Kamchatka, driven by surface temperature rises that could exceed 15°C by 2100 (Sanderson *et al.* submitted), has the potential to promote eruptions, either as a consequence of reduced load pressures on magma reservoirs or through increased opportunity for magma–water interaction. Additionally, the potential for edifice lateral collapse could be enhanced as a consequence of elevated pore-water pressures arising from meltwater and a significant predicted rise in precipitation (Capra 2006; Deeming *et al.* 2010). The potential for both volcanic and non-volcanic landslides may also be promoted by increased availability of water leading to slope destabilization and failure due to slow cracking, held to be a contributory factor in the formation of stürztzstroms (giant, rapidly moving, landslides) (e.g. Kilburn & Petley 2003).

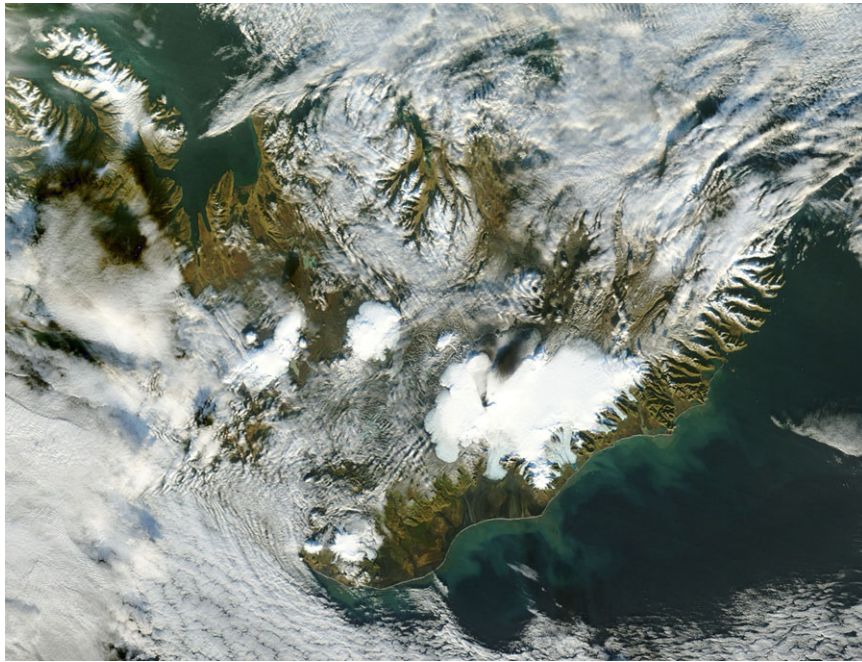


Figure 4. Iceland's Vatnajökull ice cap captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on the *Terra* satellite in November 2004. Pagli & Sigmundsson (2008) predict that reduced ice load due to future climate change will result in an additional 1.4 km^3 of melt being produced in the underlying mantle every century, comparable to an eruption equivalent in size to the 1996 Gjalp eruption beneath Vatnajökull, every 30 years. Courtesy: NASA.

An increase in climate-change-driven, non-volcanic, mass movements at high latitudes may already be apparent. Huggel (2009) and Huggel *et al.* (2008, 2010) speculate that rising temperatures may be behind a recent series of major (volumes in excess of 10^6 m^3) rock and ice avalanches in Alaska. With atmospheric warming in the state occurring at a rate of $0.03\text{--}0.05^\circ\text{C yr}^{-1}$ (Symon *et al.* 2005), a continuing trend towards the more frequent formation of large landslides is probable. Generally, a combination of melting permafrost and rising rock temperatures can reasonably be expected to increase the incidence of instability development and large-scale mass movement across all regions of elevated terrain at high latitudes.

(b) Ocean basins and margins

Warmer oceans have the potential to influence the stability of gas-hydrate deposits in marine sediments and, as a consequence, destabilize submarine slopes. Increased ocean mass, reflected in rising sea levels, may elicit volcanic and seismic responses in coastal and island settings, which in turn may promote the formation of subaerial volcanic landslides, submarine landslides and tsunamis.

Potentially sensitive to rising ocean temperatures is the stability of gas-hydrate deposits contained in marine sediments in many parts of the world (e.g. Henriot & Mienert 1998 and references therein; Bice & Marotzke 2002; Day & Maslin 2010; Maslin *et al.* 2010). These present a number of prospective

hazards, most notably through the release of enormous volumes of methane as a consequence of destabilization, but also through triggering large submarine sediment slides that may in turn generate tsunamis. Gas hydrates are ice-like solids comprising a mixture of water and gas (normally methane), whose stability is strongly dependent upon pressure–temperature conditions. They may become dissociated and release methane gas if ambient temperatures are increased or the pressure reduced. Best estimates of the amount of carbon stored in marine hydrate deposits range from 1000 to 3000 GtC (gigatonnes of carbon), which would have a major impact on planetary warming should all or part of it be released into the atmosphere. In this regard, gas-hydrate release on a major scale is believed to have occurred as a consequence of rapid warming during the Palaeogene (the PETM: Palaeocene–Eocene thermal maximum) (Dunkley Jones *et al.* 2010). Looking ahead, however, the potential for widespread marine hydrate breakdown as a consequence of anthropogenic climate change remains a matter for debate. While rising ocean temperatures will tend towards destabilizing hydrates, increasing load pressures as a result of rising sea levels will act in the opposite sense. Maslin *et al.* (2010) note that, even if marine hydrate dissociation is triggered on a large scale, it may be that all or much of the methane released will not reach the atmosphere because either (i) thermal penetration of marine sediments to the gas-hydrate interface could be sufficiently tardy as to allow a new equilibrium to become established without significant gas release or (ii) a fraction of any gas released may be oxidized in the ocean.

Gas-hydrate dissociation has been considered by some (e.g. Kayen & Lee 1992; Maslin *et al.* 1998, 2004; Sultan *et al.* 2004; Owen *et al.* 2007; Grozic 2009) as a potential trigger for major submarine sediment slides, through the release of free gas leading to high excess pore pressures and reduction of sediment shear strength. Tappin (2010) cautions, however, that evidence for such a link is largely circumstantial. In addition, from a hazard perspective, current knowledge of the physico-chemical properties of hydrates seems to indicate that they are not able to dissociate instantaneously. Lee (2009) also points out that few studies demonstrate an unambiguous link between hydrate dissociation and the triggering of a submarine landslide, and also notes that the mechanism would seem to be most likely to prevail during glacial periods when sea levels, and consequently load pressure on marine sediments, are reduced.

Modelling studies (Wallman *et al.* 1988; Nakada & Yokose 1992) have demonstrated that sea-level changes, *ca* 100 m, are capable of triggering or modulating volcanic and tectonic activity. Quidelleur *et al.* (2008) speculate that erosion and pore-pressure changes associated with rapidly rising sea levels at glacial–interglacial transitions may play a role in major lateral collapse of ocean island volcanoes. McGuire *et al.* (1997) have linked the incidence of volcanic activity in the Mediterranean region to the rate of sea-level change over the last 80 ka. They note, in particular, a significant increase in intensity of volcanism during times of very rapid Holocene sea-level rise, between 17 and 6 ka BP, broadly coincident with the catastrophic rise events of Blanchon & Shaw (1995), which saw centennial global eustatic sea-level rise rates of *ca* 5 m. Perhaps most significantly, in relation to the impact of future sea-level rise on volcanic systems, McNutt & Beavan (1987) attribute the modulation of eruptive activity at Pavlof volcano (Alaska) to the development of compressive strain beneath the volcano when adjacent sea levels are elevated, with magma being

preferentially squeezed out under these conditions. McGuire *et al.* (1997) describe finite-element modelling results demonstrating that sea-level rise adjacent to a volcanic body reduces compressive stress within the edifice. They suggest that, during times of rapid sea-level rise, this may result in the triggering of eruptions at 'charged' volcanoes, whereat magma is stored at 5 km depth or less. The findings of McNutt & Beavan (1987), McNutt (1999) and McGuire *et al.* (1997) are compatible with ocean loading resulting in a bending moment in the crust at ocean margins, leading to reduced compression at higher levels and increased compression at depth. Progressive bending at ocean margins as ocean mass increases at the expense of melting glaciers and ice sheets has the potential to trigger eruptions at 'primed' volcanoes. The volcanic response is likely to occur across a range of time scales dependent upon the nature of individual 'plumbing' systems and the availability of magma; the cumulative effect, however, would most probably be an increase in the frequency of eruptions in areas close to the marine environment. Clustering of volcanic eruptions in response to external forcing is addressed by Mason *et al.* (2004), in the context of the recognized seasonality of eruptions, with a mathematical treatment provided by Jupp *et al.* (2004).

The numbers of volcanoes potentially susceptible to crustal strain changes associated with future sea-level rise are large. Of the 550 or so volcanoes at which eruptions have been historically documented (Global Volcanism Program 2010), McGuire *et al.* (1997) determine that 57 per cent form islands or are coastally located, while a further 38 per cent are found within 250 km of a coastline. When or if rising sea levels will result in a recognizable signal in the intensity of global volcanism remains a matter for debate. It is notable, however, that a 2 m rise by 2100 would result in a cumulative load pressure on the sea floor (20 kPa) that is an order of magnitude greater than that held responsible by McNutt & Beavan (1987) and McNutt (1999) for modulation of Pavlof's eruptive behaviour.

Nakada & Yokose (1992) have demonstrated theoretically that the large (*ca* 100 m) sea-level changes associated with glaciation–deglaciation cycles, and resulting in cumulative ocean loading/unloading of *ca* 1 MPa, are capable of triggering tectonic and volcanic activity, particularly at island arcs where the lithosphere is relatively thin. At the other extreme, Rubinstein *et al.* (2008) have correlated episodes of slow fault slip and accompanying seismic tremor at subduction zones in Cascadia (Pacific North West) and Japan with the rise and fall of ocean tides, involving peak-to-peak load-pressure changes of 15 kPa. Wilcock (2001) provides convincing evidence for micro-earthquakes on the Endeavour segment of the Juan de Fuca Ridge (northeast Pacific) being triggered by the loading effect of ocean tides, which result in vertical stress variations of 30–40 kPa. Guillas *et al.* (2010) propose that ocean load-pressure fluctuations as small as a few kilopascals modulate micro-seismicity on the East Pacific Rise.

Provided the crust is sufficiently permeable, increased water load is capable of raising pore-fluid pressure in active fault zones, thereby modulating or triggering seismicity through reducing the frictional resistance to fault slip. This mechanism has long been recognized in relation to the filling of reservoirs (Talwani 1997), and has been held responsible for a lethal earthquake that followed the Koyna reservoir in India in the early 1960s (Simpson *et al.* 1988). Pore-pressure changes in oceanic or submerged continental crust arising from a 1–2 m global sea-level rise this century would be orders of magnitude smaller than those associated with filling of reservoirs. Nevertheless, they must be considered as having the potential to trigger

earthquakes on faults that are already critically stressed and, therefore, close to rupture. This in turn provides a means for generating submarine landslides and/or tsunamis, both of which carry threats to coastal communities.

(c) *Mountainous terrain*

As for elevated topography at high latitudes, the principal impact of climate change in mountainous terrain is expected to be an increase in slope instability, the formation of ice and/or rock avalanches and debris flows and, in the Himalayas in particular, a rise in the number and size of glacial outburst floods. Primary drivers are rising rock temperatures and permafrost thaw, the latter of which is a critical mechanism via which climate is able to control slope stability and natural hazard potential in mountainous terrain (Gruber & Haeberli 2007). As described by Liggins *et al.* (2010), the European and New Zealand Alpine ranges, the Pyrenees, Caucasus, Andes and Himalayas are all expected to experience rises in mean temperature, with extreme precipitation and temperature events increasing in both magnitude and frequency.

As mentioned previously, Huggel *et al.* (2008, 2010) speculate that a recent series of major rock and ice avalanches in Alaska may be a reflection of rising temperatures associated with climate change. These include an ice and rock avalanche with a volume of $ca\ 50 \times 10^6\ m^3$ formed from the failure of the summit glacier on Mount Steller in 2005, which travelled 9 km. The authors also note a trend towards increasing slope instability in the Russian Caucasus, reflected in the collapse of part of the Dzhimarai-Khokh mountain onto the Kolka glacier in 2002 (figure 5). The resulting ice and rock avalanche entrained almost the entire glacier, accumulating a total volume of $100 \times 10^6\ m^6$ travelling at a velocity of up to $80\ ms^{-1}$ (Huggel *et al.* 2005). The avalanche transformed into a debris flow at lower altitudes, which took the lives of more than 100 people. Huggel (2009) speculates that warming permafrost may have been implicated in the failure process. During the twentieth century, permafrost has warmed by between 0.5 and $0.8^\circ C$ in the upper tens of metres (Gruber *et al.* 2004). Permafrost thaw has also been blamed for anomalous rock-fall activity in the Alps during the 2003 heatwave (Gruber & Haeberli 2007), and can reasonably be expected to drive increased slope destabilization and failure in frozen terrain at many mountain ranges as the global average temperatures continue to rise. As noted by Keiler *et al.* (2010), mountain regions are particularly sensitive to climate change as a consequence of strong feedback mechanisms involving snow cover at high elevations and albedo and heat budgets, which act to amplify change. In the European Alps, for example, temperatures have already risen by twice the global average since the late nineteenth century (Keiler *et al.* 2010).

Increased slope instabilities in some mountainous regions are also likely to be a consequence of a projected rise in the incidence of extreme precipitation events and the large-scale melting of glaciers and ice fields. Episodes of exceptional rainfall across elevated terrain have been shown to be effective at mobilizing rock and regolith to form destructive and lethal debris flows and debris-laden floods. Notable recent events include the 1999 alluvial fan debris flows, which claimed in excess of 30 000 lives in northern Venezuela (Swiss Re 2000), the debris flows and landslides in Italy and Switzerland the following year, which resulted in 37 deaths (Swiss Re 2001), and more than 200 mass movements associated with the major



Figure 5. On 20 September 2002, collapse of part of the Dzhimarai-Khokh peak onto the Kolka glacier (Caucasus, Russia) generated an avalanche of ice and debris that travelled 24 km, buried villages and took more than 100 lives. This image, acquired a week later, shows a long, dark grey streak running upward through the centre of the scene, marking the position of a gorge now infilled with ice and debris from the avalanche. Courtesy: NASA. Image by Robert Simmon and Jesse Allen, based on data from the NASA/GSFC/MITI/ERSDAC/JAROS, and US/Japan ASTER Science Team and MODIS Science Team.

floods in the European Alps in 2005 (Keiler *et al.* 2010). Chiarle *et al.* (2007) recognize three types of events that lead to debris flows in the Alps, but which have general application to their formation in mountainous regions: (i) intense and prolonged rainfall, leading to the saturation and failure of debris accumulations; (ii) short-duration rainstorms capable of destabilizing a glacier drainage system; and (iii) glacial lake outbursts or the melting of surface ice fields or buried ice during dry conditions. In a warmer world, all three scenarios are more likely in response to more extreme precipitation events and rising temperatures.

As temperatures rise and glaciers retreat, so a landscape is exposed that is more prone to disturbance from rising temperatures and extreme precipitation events. In the European Alps, for example, close to 50 per cent of the area previously covered by ice has been uncovered since 1850 (Zemp *et al.* 2006). Keiler *et al.* (2010) highlight the increased threat from glacial lake floods and from landslides and debris flows originating at steep, water-saturated, slopes that were previously ice-covered. In particular, outburst floods from pro-glacial lakes impounded behind ice barriers, terminal moraines or landslides pose an increasing and serious threat in many glaciated regions. Glacial lake outburst floods (GLOFs) have been historically documented from many mountainous regions, including the European Alps (Huggel *et al.* 2002), the Andes (Reynolds 1992) and the Himalayas (Watanabe & Rothacher 1996), and have claimed thousands of lives in the Andes and Himalayas alone (Clague 2009).

GLOFs are a growing hazard in the Himalayas, presenting an increasing threat to communities and infrastructure in Bangladesh, Bhutan, China, India, Nepal and Pakistan. In Nepal, an outburst flood in 1985 resulted in five deaths and the destruction of a hydropower plant (Horstmann 2004), while another in Bhutan in 1994 took 27 lives (Watanabe & Rothacher 1996). Nepal appears to be particularly at risk, with 20 potentially dangerous glacial lakes identified, including Tsho Rolpa, the largest moraine-dammed pro-glacial lake in the region. The lake has grown sixfold since the 1950s and is fed by the Tradkarding Glacier, which is retreating at an annual rate of up to 100 m (Rana *et al.* 2000). A future GLOF from the lake threatens 10 000 people and significant infrastructure, including the 60 MW Khimti hydropower facility (Horstmann 2004). GLOFs also present a problem elsewhere, including Switzerland, where six new pro-glacial lakes developed as a consequence of retreat of the Grubengletscher Glacier in Wallis Canton. One of these drained catastrophically in 1968 and again in 1970, resulting in damaging debris flows (Haeberli *et al.* 2001). GLOFs are also becoming increasingly common in the Andes, where five outbursts occurred in northern Patagonia (Chile) in 2008 and 2009 (Dussailant *et al.* in press). In addition to promoting GLOFs through glacier melting, future warming may also increase peak discharge of outbursts when they occur. Ng *et al.* (2007) have demonstrated that peak discharge of GLOFs originating at Merzbacher Lake in Kyrgyzstan is modulated by mean air temperature, which influences the rate of meltwater input to the lake as it drains, and by the lake water temperature. The corollary, the authors note, is that future warming can be expected to promote 'higher impact' GLOFs from pro-glacial lakes worldwide, by increasing the probability of warm weather during their formation.

The moraine dams that impound most pro-glacial lakes are particularly vulnerable to failure because they are composed of loose sediment and debris, and have characteristically steep slopes that are easily destabilized. Failure may

be promoted by strong ground motion associated with earthquakes, and such a mechanism has been proposed to explain a 2.5 km^3 volume Late Pleistocene outburst of Lake Zurich (Strasser *et al.* 2008). Interestingly, the seismic threat to moraine dams may itself be increased as a consequence of the loss of ice mass promoting elevated levels of seismicity. Seismic events related to ice-mass loss may also trigger avalanches or landslides capable of displacing pro-glacial lake waters, leading to tsunamis or splash waves, moraine dam overtopping or erosion. Seismogenic landslides may also form natural dams, impounding glacial meltwater and forming new lakes that provide potential sources for future GLOFs. Probably the best-known such event occurred in the Gorno-Badakhshan province of Tajikistan in 1911, when an earthquake-triggered landslide blocked the Murghab River, forming Lake Sarez. The lake now has a volume of around 16 km^3 , and presents a serious threat to communities downstream should the rock dam become breached.

(d) *Volcanic landscapes*

The disposition of tectonic plates ensures a non-random distribution of active volcanoes, with large concentrations at high latitudes (Alaska, Kamchatka, Iceland) and in the tropics (Indonesia, Papua New Guinea, the Philippines). High-latitude volcanoes are often glaciated and typically susceptible to the same deglaciation-related hazard encountered in mountainous terrains of non-volcanic origin. As addressed in detail by Tuffen (2010), a number of questions remain unanswered in relation to the impact of ice-mass loss from glaciated volcanoes. Where volcanoes are buried beneath a significant ice thickness, as at Iceland's Vatnajökull, large-scale melting due to climate change is convincingly predicted to lead to increased mantle melting and eruptive activity (Pagli & Sigmundsson 2008) as a consequence of unloading. In relation to smaller ice volumes capping individual edifices, most notably in Alaska, Kamchatka, the Andes, the Cascades and New Zealand, any unloading effect is likely to be negligible. Tuffen (2010) observes, however, that ice thinning of 100 m or more at volcanoes with ice cover in excess of 150 m, such as Sollipulli (Chile), may promote more explosive eruptions, with increased tephra hazards. Notwithstanding the influence of unloading, other hazardous consequences of ice melting are likely to be significant. These include GLOFs, ice avalanches and lateral collapse events. GLOFs may arise from the catastrophic release of meltwater from the overtopping or breaching of crater lakes or depressions, particularly where the water is impounded by weak pyroclastic material. Such an event occurred at Ruapehu (New Zealand) in 2007, when a tephra 'dam' holding back impounded water in a crater lake was breached, generating a debris-rich flood with an estimated volume of $1.4 \times 10^6 \text{ m}^3$ (Carrivick *et al.* 2009b). As ice is progressively lost from glaciated volcanoes, however, the GLOF threat is likely to fall. The growing incidence of large-volume ice avalanches at active volcanoes, most notably in Alaska (Huggel *et al.* 2008), can reasonably be expected to increase as ice masses weakened by rising air temperatures are further perturbed by geothermal heat (Huggel 2009). A general rise in edifice instability leading to greater potential for lateral collapse may also be promoted by ice-mass loss at glaciated volcanoes. As noted by Tuffen (2010), this may arise due to debuttressing and withdrawal of mechanical support previously supplied by the ice, or as a consequence of meltwater saturation raising pore-water

pressures within shallow hydrothermal systems, which may—in turn—promote slip on established planes of weakness (Capra 2006). While a progressive loss of ice mass at glaciated volcanoes is likely to result in a reduction in the incidence of GLOF-related debris flows, higher-magnitude intense precipitation events across deglaciated and unglaciated volcanic landscapes may have the opposite effect, particularly at volcanoes in northern mid-latitudes and the southern tropics and subtropics, which are already becoming wetter as a consequence of anthropogenic climate change (Zhang *et al.* 2007). Mobilization of poorly consolidated debris exposed by retreating ice may, in particular, provide a source for potentially destructive debris flows.

In unglaciated high-relief volcanic regions, including in the Caribbean, Europe, Indonesia, the Philippines and Japan, climate change may drive increased hazardous activity via modified precipitation patterns and, in particular, a rise in the frequency and magnitude of severe rainfall events. The main hazard ramifications are likely to be an increase in debris flow production and an elevated potential for the development of slope instability and landslides due to rises in pore-water pressure. Two recent incidents demonstrate the destructiveness and lethality of precipitation-triggered collapses and debris flows (also known as lahars) in volcanic landscapes. In 1998 at Sarno (Campania, Italy), sustained, extreme, rainfall mobilized pyroclastic material derived from the Vesuvius and Campi Flegrei volcanic centres, leading to the formation of *ca* 150 debris flows, which resulted in 160 fatalities and extensive damage to Sarno and neighbouring population centres (Brondi & Salvatori 2003). Later the same year, torrential precipitation associated with Hurricane Mitch triggered a small flank collapse at Casita volcano (Nicaragua) (Scott *et al.* 2005). The resulting landslide rapidly transformed into a watery debris flood and then into a debris flow that inundated two towns and took 2500 lives. Looking ahead, many volcanoes provide a ready source of unconsolidated debris that can be rapidly transformed into potentially hazardous debris flows by extreme precipitation events that are predicted to become broadly more common as a consequence of planetary warming. Notably, as for Casita, many volcanoes occupying coastal, near-coastal or island locations in the tropics are particularly susceptible to torrential rainfall associated with tropical cyclones, which are projected by some to become both more powerful (e.g. Emanuel *et al.* 2008) and wetter (e.g. Knutson *et al.* 2008).

5. Conclusions

Evidence from the study of periods of exceptional climate change, together with contemporary observations, supports a robust link between changing climatic conditions and a broad portfolio of potentially hazardous geological and geomorphological processes. Modelling studies and the projection of current trends argue for elevated levels of a range of geological and geomorphological hazards in a warmer world, while viable physical mechanisms capable of eliciting a geospheric reaction in response to small changes in environmental conditions are well established. Questions remain, however, most particularly in relation to the time scales over which a geospheric response may be detectable. Although increases in the incidence of climate-change-driven, large-volume rock and ice avalanches (Huggel *et al.* 2008, 2010; Huggel 2009), and the suggested modulation

of seismicity in areas of large-scale ice wastage (Sauber & Molnia 2004; Sauber & Ruppert 2008), lead to speculation that climate change is already drawing out a crustal response, no increase in the global incidence of either volcanic activity or seismicity has been identified to date, nor has any change in the stability of submarine slopes been detected. It may be the case that modulation of potentially hazardous geological and geomorphological processes due to anthropogenic climate change proves to be too small a signal to extract from the background noise of 'normal' geophysical activity, at least in the short to medium term.

Furthermore, there are few constraints on the timing of a geospheric response, which may well lag significantly behind the warming trend. With respect to ice wastage in Greenland and Antarctica, Turpeinan *et al.* (2008) and Hampel *et al.* (2010) suggest that enhanced seismicity may be important on time scales as short as 10–100 years. A comparable time scale has been proposed (Gruber *et al.* 2004; Harris *et al.* 2009) in relation to the formation of large, deep-rooted, landslides following temperature rise and permafrost thaw in mountain regions. With respect to increased levels of melt production in the mantle beneath Iceland's Vatnajökull ice cap, Sigmundsson *et al.* (2010) speculate that it could take centuries or longer for fresh magma to reach the surface. There is also considerable uncertainty in relation to the linearity of possible responses, with different elements of the geosphere responding, for example, in a nonlinear manner, with thresholds or tipping points resulting in step-like increases in frequency or scale.

In order to improve knowledge and reduce uncertainty, a programme of focused research is advocated so as to understand better those mechanisms by which contemporary climate change may drive hazardous geological and geomorphological activity, to delineate those parts of the world that are most susceptible, and to provide a more robust appreciation of potential impacts for society and infrastructure. More specifically, there is a need to: (i) better establish potential correlations in the geological (particularly the Quaternary) record, between climate change and significant hazardous events such as large submarine landslides, major volcanic eruptions and ocean island collapses; (ii) promote the application of modelling techniques so as to investigate, and more accurately portray, the influences of changing environmental conditions such as ice-mass wastage and ocean loading on potentially hazardous geophysical systems; and (iii) encourage monitoring of specific locations perceived already to be demonstrating a climate-change response or that are deemed sensitive enough to do so in the short to medium term. The IPCC is also strongly exhorted to address more explicitly, in future assessments, the impact of anthropogenic climate change on the geosphere, together with its manifold potentially hazardous consequences.

Among a number of colleagues and others whose thoughts and suggestions have helped to improve this paper considerably from earlier versions, Dave Tappin is particularly acknowledged.

References

- Alho, P., Russell, A. J., Carrivick, J. L. & Kayhko, J. 2005 Reconstruction of the largest Holocene jokulhlaup within Jokulsa a Fjollum, NE Iceland. *Quat. Sci. Rev.* **24**, 2319–2334. (doi:10.1016/j.quascirev.2004.11.021)
- Anderson, D. C. 1974 Earthquakes and the rotation of the Earth. *Science* **186**, 49–50. (doi:10.1126/science.186.4158.49)

- Andrews, J. T. 1973 The Wisconsin Laurentide ice sheet: dispersal centres, problems of rates of retreat, and climatic implications. *Arctic Alpine Res.* **5**, 185–199. (doi:10.2307/1550028)
- Bay, R., Bramall, N. & Price, P. 2004 Bipolar correlation of volcanism with millennial climate change. *Proc. Natl Acad. Sci. USA* **101**, 6341–6345. (doi:10.1073/pnas.0400323101)
- Beget, J. E. & Addison, J. A. 2007 Methane gas release from the Storegga submarine landslide linked to early-Holocene climate changes: a speculative hypothesis. *Holocene* **17**, 291–295. (doi:10.1177/0959683607076435)
- Bettinelli, P., Avouac, J.-P., Flouzat, M., Bollinger, L., Ramillien, G., Rajaure, S. & Sapkota, S. 2008 Seasonal variations of seismicity and geodetic strain in the Himalaya induced by surface hydrology. *Earth Planet. Sci. Lett.* **266**, 332–344. (doi:10.1016/j.epsl.2007.11.021)
- Betts, R. A., Collins, M., Hemming, D. H., Jones, C. D., Lowe, J. A. & Sanderson, M. Submitted. When could global warming reach 4°C? *Phil. Trans. R. Soc. A*.
- Bice, K. L. & Marotzke, J. 2002 Could changing ocean circulation have destabilized methane hydrate at the Paleocene/Eocene boundary? *Paleoceanography* **17**, 1018. (doi:10.1029/2001PA000678)
- Bigg, G., Clark, C. & Hughes, A. 2008 A last glacial ice sheet on the Pacific Russian coast and catastrophic change arising from coupled ice–volcanic interaction. *Earth Planet. Sci. Lett.* **265**, 559–570. (doi:10.1016/j.epsl.2007.10.052)
- Blanchon, P. & Shaw, J. 1995 Reef drowning during the last glaciation: evidence for catastrophic sea-level rise and ice-sheet collapse. *Geology* **23**, 4–8. (doi:10.1130/0091-7613(1995)023<0004:RDDTLD>2.3.CO;2)
- Bondevik, S., Lovholt, F., Harvitz, C., Mangerud, J., Dawson, A. & Svendsen, J. I. 2005 The Storegga Slide tsunami—comparing field observations with numerical simulations. *Mar. Pet. Geol.* **22**, 195–208. (doi:10.1016/j.marpetgeo.2004.10.003)
- Brondi, F. & Salvatori, L. 2003 The 5–6 May 1998 mudflows in Campania, Italy. In *Lessons learned from landslide disasters in Europe* (ed. J. Hervás), pp. 5–16. Brussels, Belgium: European Commission Joint Research Centre.
- Bryn, P., Berg, K., Forsberg, C. F., Solheim, A. & Kvalstad, T. J. 2005 Explaining the Storegga Slide. *Mar. Pet. Geol.* **22**, 11–19. (doi:10.1016/j.marpetgeo.2004.12.003)
- Capra, L. 2006 Abrupt climate changes as triggering mechanisms of massive volcanic collapses. *J. Volcanol. Geotherm. Res.* **155**, 329–333. (doi:10.1016/j.jvolgeores.2006.04.009)
- Carrivick, J. L., Russell, A. J., Rushmer, E. L., Tweed, F. S., Marren, P. M., Deeming, H. & Lowe, O. J. 2009a Geomorphological evidence towards a deglacial control on volcanism. *Earth Surf. Process. Landf.* **34**, 1164–1178. (doi:10.1002/esp.1811)
- Carrivick, J. L., Manville, V. & Cronin, S. J. 2009b A fluid dynamics approach to modelling the 18th March 2007 lahar at Mt Ruapehu, New Zealand. *Bull. Volcanol.* **71**, 153–169. (doi:10.1007/s00445-008-0213-2)
- Chappel, J. 1975 On possible relationships between Upper Quaternary glaciations, geomagnetism and volcanism. *Earth. Planet. Sci. Lett.* **26**, 370–376. (doi:10.1016/0012-821X(75)90013-8)
- Chiarle, M., Iannotti, S., Mortara, G. & Deline, P. 2007 Recent debris flow occurrences associated with glaciers in the Alps. *Global Planet. Change* **56**, 123–136. (doi:10.1016/j.gloplacha.2006.07.003)
- Christensen, J. H. *et al.* 2007 Regional climate predictions. In *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller), pp. 847–940. Cambridge, UK: Cambridge University Press.
- Christiansen, L. B., Hurwitz, S., Saar, M. O., Ingebritsen, S. E. & Hsieh, P. A. 2005 Seasonal seismicity at western United States volcanic centers. *Earth Planet. Sci. Lett.* **240**, 307–321. (doi:10.1016/j.epsl.2005.09.012)
- Christiansen, L. B., Hurwitz, S. & Ingebritsen, S. 2007 Annual modulation of seismicity along the San Andreas Fault near Parkfield, CA. *Geophys. Res. Lett.* **34**, L04306. (doi:10.1029/2006GL028634)

- Clague, J. J. 2009 Climate change and slope instability. In *Landslides—disaster risk reduction. 1st World Landslide Forum 2008* (eds K. Sassa & P. Canuti), pp. 557–572. Tokyo, Japan: UN University.
- Costain, J. K. & Bollinger, G. A. 1996 Climatic changes, streamflow, and long-term forecasting of intraplate seismicity. *J. Geodyn.* **22**, 97–117. (doi:10.1016/0264-3707(96)00007-5)
- Davenport, C. A., Ringrose, P. S., Becker, A., Hancock, P. & Fenton, C. 1989 In *Earthquakes at North-Atlantic passive margins: neotectonics and post-glacial rebound* (eds J. Gregersen & P. W. Basham). NATO Advanced Science Institute Series C, Mathematical and Physical Sciences, vol. 266, pp. 175–194. Dordrecht, The Netherlands: Kluwer.
- Day, S. J. & Maslin, M. 2010 Gas hydrates: a hazard for the twenty-first century? *Phil. Trans. R. Soc. A* **368**, 2579–2583. (doi:10.1098/rsta.2010.0066)
- Day, S. J., McGuire, W. J., Elsworth, D., Carracedo, J.-C. & Guillou, H. 1999 Do giant collapses of volcanoes tend to occur in warm, wet, interglacial periods and if so, why? *Abstract volume, week B, IUGG XXII General Assembly, Birmingham, UK*, p. 174.
- Day, S. J., Elsworth, D. & Maslin, M. 2000 A possible connection between sea-surface temperature variations, orographic rainfall patterns, water-table fluctuations and giant lateral collapses of the oceanic island volcanoes. *Abstract volume, Western Pacific Geophysics Meeting, Tokyo, Japan*, WP251.
- Deeming, K. R., McGuire, B. & Harrop, P. 2010 Climate forcing of volcano lateral collapse: evidence from Mount Etna, Sicily. *Phil. Trans. R. Soc. A* **368**, 2559–2577. (doi:10.1098/rsta.2010.0054)
- Doser, D. I., Wiest, K. R. & Sauber, J. 2007 Seismicity of the Bering Glacier region and its relation to tectonic and glacial processes. *Tectonophysics* **439**, 119–127. (doi:10.1016/j.tecto.2007.04.005)
- Dunkley Jones, T., Ridgwell, A., Lunt, D. J., Maslin, M. A., Schmidt, D. N. & Valdes, P. J. 2010 A Palaeogene perspective on climate sensitivity and methane hydrate instability. *Phil. Trans. R. Soc. A* **368**, 2395–2415. (doi:10.1098/rsta.2010.0053)
- Dussailant, A., Benito, G., Buytaert, W., Carling, P., Meier, C. & Espinoza, F. In press. Repeated glacial-lake outburst floods in Patagonia: an increasing hazard? *Nat. Haz.* (doi:10.1007/s11069-009-9479-8)
- Ekstrom, G., Nettles, M. & Tsai, V. C. 2003 Seasonality and increasing frequency of Greenland glacial earthquakes. *Science* **311**, 1756–1758. (doi:10.1126/science.1122112)
- Emanuel, K., Sundararajan, R. & Williams, J. 2008 Hurricanes and global warming. *Bull. Am. Meteorol. Soc.* **89**, 347–367. (doi:10.1175/BAMS-89-3-347)
- Frieler, P. A. & Clague, J. J. 2004 Large Holocene landslides from Pylon Peak, southwestern British Columbia. *Can. J. Earth Sci.* **41**, 165–182. (doi:10.1139/e03-089)
- Frisia, S., Borsato, A., Mangini, A., Spötl, C., Madonia, G. & Sauro, U. 2006 Holocene climate variability in Sicily from a discontinuous stalagmite record and the Mesolithic to Neolithic transition. *Quat. Res.* **66**, 388–400. (doi:10.1016/j.yqres.2006.05.003)
- Glazner, A. F., Manley, C. R., Marron, J. S. & Rojstaczer, S. 1999 Fire or ice: anticorrelation of volcanism and glaciation in California over the past 800 000 years. *Geophys. Res. Lett.* **26**, 1759–1762. (doi:10.1029/1999GL900333)
- Global Volcanism Program. 2010 Worldwide Holocene volcano and eruption information. Smithsonian National Museum of Natural History, Washington, USA. See <http://www.volcano.si.edu/>.
- Grattan, J., Rabartin, R., Self, S. & Thordarson, T. 2005 Volcanic air pollution and mortality in France 1783–1784. *C. R. Geosci.* **337**, 641–651. (doi:10.1016/j.crte.2005.01.013)
- Grozic, J. L. H. 2009 Interplay between gas hydrates and submarine slope failure. In *Submarine mass movements and their consequences* (eds D. C. Mosher, R. C. Shipp, L. Moscardelli, J. D. Chaytor, C. D. P. Baxter, H. J. Lee & R. Urgeles). Advances in Natural and Technological Hazards Research 28, pp. 11–30. Dordrecht, The Netherlands: Springer.
- Gruber, S. & Haeblerli, W. 2007 Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *J. Geophys. Res.* **112**, F02S18. (doi:10.1029/2006JF000547)

- Gruber, S., Hoelzle, M. & Haeblerli, W. 2004 Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003. *Geophys. Res. Lett.* **31**, L13504. (doi:10.1029/2004GL020051)
- Guillas, S., Day, S. J. & McGuire, B. 2010 Statistical analysis of El Niño–Southern Oscillation and sea-floor seismicity in the eastern tropical Pacific. *Phil. Trans. R. Soc. A* **368**, 2481–2500. (doi:10.1098/rsta.2010.0044)
- Haeblerli, W., Kääh, A., Mühlh, D. V. & Teyssere, P. 2001 Prevention of outburst floods from periglacial lakes at Grubengletscher, Valais, Swiss Alps. *J. Glaciol.* **47**, 111–122. (doi:10.3189/172756501781832575)
- Hainzl, S., Kraft, T., Wassermann, J., Igel, H. & Schmedes, E. 2006 Evidence for rainfall-triggered earthquake activity. *Geophys. Res. Lett.* **33**, L19303. (doi:10.1029/2006GL027642)
- Hall, K. 1982 Rapid deglaciation as an initiator of volcanic activity: an hypothesis. *Earth Surf. Process. Landf.* **206**, 45–51. (doi:10.1002/esp.3290070106)
- Hamilton, W. 1973 Tidal cycles of volcanic eruptions: fortnightly to yearly periods. *J. Geophys. Res.* **78**, 3363–3375. (doi:10.1029/JB078i017p03363)
- Hampel, A., Hetzel, R. & Densmore, A. L. 2007 Postglacial slip rate increase on the Teton normal fault, northern Basin and Range Province, caused by melting of the Yellowstone ice cap and deglaciation of the Teton Range? *Geology* **35**, 1107–1110. (doi:10.1130/G24093A.1)
- Hampel, A., Hetzel, R. & Maniatis, G. 2010 Response of faults to climate-driven changes in ice and water volumes on Earth's surface. *Phil. Trans. R. Soc. A* **368**, 2501–2517. (doi:10.1098/rsta.2010.0031)
- Harris, C. *et al.* 2009 Permafrost and climate in Europe: monitoring and modelling thermal, geomorphological and geotechnical responses. *Earth Sci. Rev.* **92**, 117–171. (doi:10.1016/j.earscirev.2008.12.002)
- Heki, K. 2003 Snow load and seasonal variation of earthquake occurrence in Japan. *Earth Planet. Sci. Lett.* **207**, 159–164. (doi:10.1016/S0012-821X(02)01148-2)
- Hély, C., Braccanot, P., Watrin, J. & Zheng, W. 2009 Climate and vegetation: simulating the African humid period. *C. R. Geosci.* **341**, 671–688. (doi:10.1016/j.crte.2009.07.002)
- Henriet, J.-P. & Mienert, J. (eds) 1998 *Gas hydrates: relevance to world margin stability and climate change*. Geological Society Special Publication no. 137, p. 338. London, UK: Geological Society.
- Hermanns, R. L., Niedermann, S., Ivy-Ochs, S. & Kubik, P. W. 2004 Rock avalanching into a landslide-dammed lake causing multiple dam failure in Las Conchas valley (NW Argentina)—evidence from surface exposure dating and stratigraphic analyses. *Landslides* **1**, 113–122. (doi:10.1007/s10346-004-0013-5)
- Hetzel, R. & Hampel, A. 2005 Slip rate variations on normal faults during glacial–interglacial changes in surface loads. *Nature* **435**, 81–84. (doi:10.1038/nature03562)
- Horstmann, B. 2004 *Glacial lake outburst floods in Nepal and Switzerland*, p. 12. Bonn, Germany: Germanwatch.
- Huggel, C. 2009 Recent extreme slope failures in glacial environments: effects of thermal perturbation. *Quat. Sci. Rev.* **28**, 1119–1130. (doi:10.1016/j.quascirev.2008.06.007)
- Huggel, C., Kääh, A., Haeblerli, W., Teyssere, P. & Paul, F. 2002 Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Can. Geotech. J.* **39**, 316–330. (doi:10.1139/t01-099)
- Huggel, C., Zraggen-Oswald, S., Haeblerli, W., Kääh, A., Polkvoj, A., Galushkin, I. & Evans, S. G. 2005 The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche formation and mobility, and application of QuickBird satellite imagery. *Nat. Haz. Earth Syst. Sci.* **5**, 173–187. (www.nat-hazards-earth-syst-sci.net/5/173/2005/)
- Huggel, C., Caplan-Auerbach, J. & Wessels, R. 2008 Recent extreme avalanches: triggered by climate change? *Eos, Trans. AGU* **89**, 469–470. (doi:10.1029/2008EO470001)
- Huggel, C., Salzmann, N., Allen, S., Caplan-Auerbach, J., Fischer, L., Haeblerli, W., Larsen, C., Schneider, D. & Wessels, R. 2010 Recent and future warm extreme events and high-mountain slope stability. *Phil. Trans. R. Soc. A* **368**, 2435–2459. (doi:10.1098/rsta.2010.0078)
- Huybers, P. & Langmuir, C. 2009 Feedback between deglaciation, volcanism and atmospheric CO₂. *Earth Planet. Sci. Lett.* **286**, 479–491. (doi:10.1016/j.epsl.2009.07.014)

- IPCC. 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* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller), p. 996. Cambridge, UK: Cambridge University Press.
- Jellinek, A., Manga, M. & Saar, M. 2004 Did melting glaciers cause volcanic eruptions in eastern California? Probing the mechanics of dike formation. *J. Geophys. Res.* **109**, B09206. (doi:10.1029/2004JB002978)
- Johnston, A. C. 1987 Suppression of earthquakes by large continental ice sheets. *Nature* **330**, 467–469. (doi:10.1038/330467a0)
- Johnston, M. & Mauk, F. 1972 Earth tides and the triggering of eruptions from Mount Stromboli. *Nature* **239**, 266–267. (doi:10.1038/239266b0)
- Jull, M. & McKenzie, D. 1996 The effect of deglaciation on mantle melting beneath Iceland. *J. Geophys. Res.* **101**, 21 815–21 828. (doi:10.1029/96JB01308)
- Jupp, T., Pyle, D., Mason, B. & Dade, W. 2004 A statistical model for the timing of earthquakes and volcanic eruptions influenced by periodic processes. *J. Geophys. Res.* **109**, B02206. (doi:10.1029/2003JB002584)
- Kayen, R. E. & Lee, H. J. 1992 Pleistocene slope instability of gas hydrate-laden sediment on the Beaufort Sea margin. *Mar. Geotechnol.* **10**, 125–142.
- Keating, B. H. & McGuire, W. J. 2004 Instability and structural failure at volcanic ocean islands and the climate change dimension. *Adv. Geophys.* **47**, 175–271.
- Keefer, D. K., Moseley, M. E. & de France, S. D. 2000 A 38 000-year record of floods and debris flows in the Ilo region of southern Peru and its relation to El Niño events and great earthquakes. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **194**, 41–77. (doi:10.1016/S0031-0182(03)00271-2)
- Keiler, M., Knight, J. & Harrison, S. 2010 Climate change and geomorphological hazards in the eastern European Alps. *Phil. Trans. R. Soc. A* **368**, 2461–2479. (doi:10.1098/rsta.2010.0047)
- Kennett, J. & Thunell, R. 1975 Global increase in Quaternary explosive volcanism. *Science* **187**, 497–503. (doi:10.1126/science.187.4176.497)
- Kilburn, C. R. J. & Petley, D. N. 2003 Forecasting giant, catastrophic slope collapse: lessons from Vajont, northern Italy. *Geomorphology* **54**, 21–32. (doi:10.1016/S0169-555X(03)00052-7)
- Knutson, T., Sirutis, J., Garner, S., Vecchi, G. & Held, I. 2008 Simulated reduction in Atlantic hurricane frequency under twenty-first century warming conditions. *Nat. Geosci.* **1**, 359–364. (doi:10.1038/ngeo202)
- Lateltin, O., Beer, C., Raetzo, H. & Caron, C. 1997 Landslides in flysch terranes of Switzerland: causal factors and climate change. *Eclogae Geol. Helv.* **90**, 401–406.
- Lee, H. J. 2009 Timing of occurrence of large submarine landslides on the Atlantic Ocean margin. *Mar. Geol.* **264**, 53–64. (doi:10.1016/j.margeo.2008.09.009)
- Licciardi, J., Kurz, M. & Curtice, J. 2007 Glacial and volcanic history of Icelandic table mountains from cosmogenic ³He exposure ages. *Quat. Sci. Rev.* **26**, 1529–1546. (doi:10.1016/j.quascirev.2007.02.016)
- Liggins, F., Betts, R. A. & McGuire, B. 2010 Projected future climate changes in the context of geological and geomorphological hazards. *Phil. Trans. R. Soc. A* **368**, 2347–2367. (doi:10.1098/rsta.2010.0072)
- Liu, C., Linde, A. T. & Sacks, I. S. 2009 Slow earthquakes triggered by typhoons. *Nature* **459**, 833–836. (doi:10.1038/nature08042)
- MacLennan, J., Jull, M., McKenzie, D., Slater, L. & Grönvold, K. 2002 The link between volcanism and deglaciation in Iceland. *Geochem. Geophys. Geosyst.* **11**, 1062. (doi:10.1029/2001GC000282)
- Maslin M. A., Mikkelsen, N., Vilela, C. & Haq, B. 1998 Sea-level- and gas-hydrate-controlled catastrophic sediment failures of the Amazon Fan. *Geology* **26**, 1107–1110. (doi:10.1130/0091-7613(1998)026<1107:SLAGHC>2.3.CO:2)
- Maslin, M. A., Owen, M., Day, S. & Long, D. 2004 Linking continental slope failure to climate change: testing the clathrate gun hypothesis. *Geology* **32**, 53–56. (doi:10.1130/G20114.1)
- Maslin, M., Owen, M., Betts, R., Day, S., Dunkley Jones, T. & Ridgwell, A. 2010 Gas hydrates: past and future geohazard? *Phil. Trans. R. Soc. A* **368**, 2369–2393. (doi:10.1098/rsta.2010.0065)

- Mason, B., Pyle, D., Dade, W. & Jupp, T. 2004 Seasonality of volcanic eruptions. *J. Geophys. Res.* **109**, B04206. (doi:10.1029/2002JB002293)
- Masson, D. G., Watts, A. B., Gee, M. J. R., Urgeles, R., Mitchell, N. C., Le Bas, T. P. & Canals, M. 2002 Slope failures on the flanks of the western Canary Islands. *Earth Sci. Rev.* **57**, 1–35. (doi:10.1016/S0012-8252(01)00069-1)
- Mastin, L. G. 1994 Explosive tephra emissions of Mount St. Helens, 1989–1991: the violent escape of magmatic gas following storms? *Geol. Soc. Am. Bull.* **106**, 175–185. (doi:10.1130/0016-7606(1994)106<0175:ETEAMS>2.3.CO;2)
- Matthews, A. J., Barclay, J., Carn, S., Thompson, G., Alexander, J., Herd, R. & Williams, C. 2002 Rainfall-induced volcanic activity on Montserrat. *Geophys. Res. Lett.* **29**, 2211–2214. (doi:10.1029/2002GL014863)
- Matthews, R. K. 1969 Tectonic implications of glacio-eustatic sea level fluctuations. *Earth Planet. Sci. Lett.* **5**, 459–462. (doi:10.1016/S0012-821X(68)80079-2)
- Mayewski, P. A. *et al.* 2004 Holocene climate variability. *Quat. Res.* **62**, 243–255. (doi:10.1016/j.yqres.2004.07.001)
- McGuire, W. J., Howarth, R. J., Firth, C. R., Solow, A. R., Pullen, A. D., Saunders, S. J., Stewart, I. S. & Vita-Finzi, C. 1997 Correlation between rate of sea level change and frequency of explosive volcanism in the Mediterranean. *Nature* **389**, 473–476. (doi:10.1038/38998)
- McMurtry, G. M., Watts, P., Fryer, G. J., Smith, J. R. & Imamura, F. 2004 Giant landslides, mega-tsunamis, and palaeo-sea level in the Hawaiian Islands. *Mar. Geol.* **203**, 219–233. (doi:10.1016/S0025-3227(03)00306-2)
- McNutt, S. 1999 Eruptions of Pavlof volcano, Alaska, and their possible modulation by ocean load and tectonic stresses: re-evaluation of the hypothesis based on new data from 1984–1998. *Pure Appl. Geophys.* **155**, 701–712. (doi:10.1007/s000240050284)
- McNutt, S. & Beavan, R. 1987 Eruptions of Pavlof volcano and their possible modulation by ocean load and tectonic stresses. *J. Geophys. Res.* **92**, 11 509–11 523.
- Meehl, G. A. *et al.* 2007 Global climate projections. In *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller), pp. 747–846. Cambridge, UK: Cambridge University Press.
- Mernild, S. H., Hasholt, B., Kane, D. L. & Tidwell, A. C. 2008 Jökulhlaup observed at Greenland ice sheet. *Eos, Trans. AGU* **99**, 321–322. (doi:10.1029/2008EO350001)
- Muir-Wood, R. 2000 Deglaciation seismotectonics: a principal influence on intraplate seismogenesis at high latitudes. *Quat. Sci. Rev.* **19**, 1399–1411. (doi:10.1016/S0277-3791(00)00069-X)
- Nakada, M. & Yokoye, H. 1992 Ice age as a trigger of active Quaternary volcanism and tectonism. *Tectonophysics* **212**, 321–329. (doi:10.1016/0040-1951(92)90298-K)
- Nakicenovic, N. *et al.* 2000 *IPCC special report on emissions scenarios*. Cambridge, UK: Cambridge University Press.
- Neuberg, J. 2000 External modulation of volcanic activity. *Geophys. J. Int.* **142**, 232–240. (doi:10.1046/j.1365-246x.2000.00161.x)
- Ng, F., Liu, S., Mavlyudov, B. & Wang, Y. 2007 Climatic control on the peak discharge of glacier outburst floods. *Geophys. Res. Lett.* **34**, L21503. (doi: 10.1029/2007GL031426)
- Nowell, D. A. G., Jones, M. C. & Pyle, D. M. 2006 Episodic Quaternary volcanism in France and Germany. *J. Quat. Sci.* **21**, 645–675. (doi:10.1002/jqs.1005)
- Owen, M., Day, S. & Maslin, M. 2007 Late Pleistocene submarine mass movements: occurrence and causes. *Quat. Sci. Rev.* **26**, 958–978. (doi:10.1016/j.quascirev.2006.12.011)
- Pagli, C. & Sigmundsson, F. 2008 Will present day glacier retreat increase volcanic activity? Stress induced by recent glacier retreat and its effect on magmatism at the Vatnajökull ice cap, Iceland. *Geophys. Res. Lett.* **35**, L09304. (doi:10.1029/2008GL033510)
- Pagli, C., Sigmundsson, F., Lund, B., Sturkell, E., Geirsson, H., Einarsson, P., Árnadóttir, T. & Hreinsdóttir, S. 2007 Glacio-isostatic deformation around the Vatnajökull ice cap, Iceland, induced by recent climate warming: GPS observations and finite element modeling. *J. Geophys. Res.* **112**, B08405. (doi:10.1029/2006JB004421)
- Pfeffer, W. T., Harper, J. T. & O’Neel, S. 2008 Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science* **321**, 1340–1343. (doi:10.1126/science.1159099)

- Podolskiy, E. A. 2008 Effects of recent environmental changes on global seismicity and volcanism. *Earth Interact.* **13**, 1–14. (doi:10.1175/2009EI262.1)
- Pratt, B., Burbank, D. W., Heimsath, A. & Ojha, T. 2002 Impulsive alluviation during early Holocene strengthened monsoons, central Nepal Himalaya. *Geology* **30**, 911–914. (doi:10.1130/0091-7613(2002)030<0911:IADEHS>2.0.CO;2)
- Quidelleur, X., Hildenbrand, A. & Samper, A. 2008 Causal link between Quaternary palaeoclimatic changes and volcanic islands evolution. *J. Geophys. Res.* **35**, L02303. (doi:10.1029/2007GL031849)
- Rahmstorf, S. 2007 A semi-empirical approach to projecting future sea-level rise. *Science* **315**, 368–370. (doi:10.1126/science.1135456)
- Rampino, M., Self, S. & Fairbridge, R. 1979 Can rapid climate change cause volcanic eruptions? *Science* **206**, 826–828. (doi:10.1126/science.206.4420.826)
- Rana, B., Shrestha, A. B., Reynolds, J. M., Aryal, R., Pokhrel, A. P. & Budhathoki, K. P. 2000 Hazard assessment of the Tsho Rolpa glacier lake and ongoing remediation measures. *J. Nepal Geol. Soc.* **22**, 563–570.
- Reynolds, J. M. 1992 The identification and mitigation of glacier-related hazards: examples from the Cordillera Blanca, Peru. In *Geohazards* (eds G. J. H. McCall, D. J. C. Lamming & S. C. Scott), pp. 143–157. London, UK: Chapman & Hall.
- Rubinstein, J. L., La Rocca, M., Vidale, J. E., Creager, K. C. & Wech, A. G. 2008 Tidal modulation of nonvolcanic tremor. *Science* **319**, 186–189. (doi:10.1126/science.1150558)
- Saemundsson, T., Petursson, H. G. & Decaulne, A. 2003 Triggering factors for rapid mass movements in Iceland. In *Debris-flow hazards mitigation, mechanics, prediction and assessment* (eds D. Rickenmann & C. Chen), pp. 167–178. New York, NY: American Society of Civil Engineers.
- Sanderson, M. G., Hemming, D. L. & Betts, R. A. Submitted. Regional temperature and precipitation changes under high-end (>4°C) global warming. *Phil. Trans. R. Soc. A*.
- Sauber, J. & Molnia, B. F. 2004 Glacier ice mass fluctuations and fault instability in tectonically active southern Alaska. *Global Planet. Change* **42**, 279–293. (doi:10.1016/j.gloplacha.2003.11.012)
- Sauber, J. & Ruppert N. A. 2008 Rapid ice mass loss: does it have an influence on earthquake occurrence in southern Alaska? In *Active tectonics and seismic potential of Alaska* (eds J. T. Freymüller, P. J. Haeussler, R. L. Wesson & G. Ekström). Geophysical Monograph Series 179. Washington, DC: American Geophysical Union.
- Sauber, J., Plafker, G., Molnia, B. F. & Bryant, M. A. 2000 Crustal deformation associated with glacial fluctuations in the eastern Chugach Mountains, Alaska. *J. Geophys. Res.* **105**, 8055–8077. (doi:10.1029/1999JB900433)
- Schultz, W. H., Kean, J. W. & Wang, G. 2009 Landslide movement in southwest Colorado triggered by atmospheric tides. *Nat. Geosci.* **2**, 863–866. (doi:10.1038/ngeo659)
- Scott, K. M., Vallance, J. W., Kerle, N., Macías, J. L., Strauch, W. & Devoli, G. 2005 Catastrophic precipitation-triggered lahar at Casita volcano, Nicaragua: occurrence, bulking and transformation. *Earth Surf. Process. Landf.* **30**, 59–79. (doi:10.1002/esp.1127)
- Sigmundsson, F., Pinel, V., Lund, B., Albino, F., Pagli, C., Geirsson, H. & Sturkell, E. 2010 Climate effects on volcanism: influence on magmatic systems of loading and unloading from ice mass variations, with examples from Iceland. *Phil. Trans. R. Soc. A* **368**, 2519–2534. (doi:10.1098/rsta.2010.0042)
- Sigvaldason, G., Annertz, K. & Nilsson, M. 1992 Effect of glacier loading/deloading on volcanism: postglacial volcanic eruption rate of the Dyngjufjoll area, central Iceland. *Bull. Volcanol.* **54**, 385–392. (doi:10.1007/BF00312320)
- Simpson, D., Leith, W. & Scholz, C. 1988 Two types of reservoir-induced seismicity. *Bull. Seismol. Soc. Am.* **78**, 2025–2040.
- Song, T. 2009 Glacial earthquake tsunami—a consequence of climate change. In *Proceedings, 3rd Johnston–Lavis Colloquium: Climate Forcing of Geological and Geomorphological Hazards, University College London* (Abstract).
- Sparks, R. S. J. 1981 Triggering of volcanic eruptions by Earth tides. *Nature* **290**, 448. (doi:10.1038/290448a0)

- Stewart, I. S., Sauber, J. & Rose, J. 2000 Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. *Quat. Sci. Rev.* **19**, 1367–1389. (doi:10.1016/S0277-3791(00)00094-9)
- Strasser, M., Schindler, C. & Anselmetti, F. S. 2008 Late Pleistocene earthquake-triggered moraine dam failure and outburst of Lake Zurich, Switzerland. *J. Geophys. Res.* **113**, F02003. (doi:10.1029/2007JF000802)
- Sultan, N., Cochonat, P., Foucher, J.-P. & Mienert, J. 2004 Effect of gas hydrates melting on seafloor slope instability. *Mar. Geol.* **213**, 379–401. (doi:10.1016/j.margeo.2004.10.015)
- Swiss Re. 2000 Natural catastrophes and man-made disasters in 1999: storms and earthquakes lead to the second-highest losses in insurance history. Sigma No. 2/2000. Swiss Reinsurance Company, Economic Research and Consulting, Zurich, Switzerland.
- Swiss Re. 2001 Natural catastrophes and man-made disasters in 2000: fewer insured losses despite huge floods. Sigma No. 2/2001. Swiss Reinsurance Company, Economic Research and Consulting, Zurich, Switzerland.
- Symon, C., Arris, L. & Heal, B. (eds) 2005 *Arctic climate impact assessment: scientific report*. New York, NY: Cambridge University Press.
- Talwani, P. 1997 On the nature of reservoir-induced seismicity. *Pure Appl. Geophys.* **150**, 473–492. (doi:10.1007/s000240050089)
- Tappin, D. R. 2010 Submarine mass failures as tsunami sources: their climate control. *Phil. Trans. R. Soc. A* **368**, 2417–2434. (doi:10.1098/rsta.2010.0079)
- Tuffen, H. 2010 How will melting of ice affect volcanic hazards in the twenty-first century? *Phil. Trans. R. Soc. A* **368**, 2535–2558. (doi:10.1098/rsta.2010.0063)
- Turpeinen, H., Hampel, A., Karow, T. & Maniatis, G. 2008 Effect of ice sheet growth and melting on the slip evolution of thrust faults. *Earth Planet. Sci. Lett.* **269**, 230–241. (doi:10.1016/j.epsl.2008.02.017)
- Vanneste, M., Mienert, J. & Bunz, S. 2006 The Hinlopen Slide: a giant submarine slope failure on the northern Svalbard margin, Arctic Ocean. *Earth Planet. Sci. Lett.* **245**, 373–388. (doi:10.1016/j.epsl.2006.02.045)
- Wallmann, P. C., Mahood, G. A. & Pollard, D. D. 1988 Mechanical models for correlation of ring-fracture eruptions at Pantelleria, Strait of Sicily, with glacial sea-level drawdown. *Bull. Volcanol.* **50**, 327–339. (doi:10.1007/BF01073589)
- Watanabe, T. & Rothacher, D. 1996 The 1994 Lugge Tsho glacial lake outburst flood, Bhutan Himalaya. *Mount. Res. Dev.* **16**, 77–81. (doi:10.2307/3673897)
- Wilcock, W. 2001 Tidal triggering of micro earthquakes on the Juan de Fuca Ridge. *Geophys. Res. Lett.* **28**, 3999–4002. (doi:10.1029/2001GL013370)
- Wu, P. 1999 Intraplate earthquakes and postglacial rebound in eastern Canada and northern Europe. In *Dynamics of the Ice Age Earth, a modern perspective* (ed. P. Wu), pp. 443–458. Zurich, Switzerland: Trans Tech.
- Wu, P. & Johnston, P. 2000 Can deglaciation trigger earthquakes in N. America? *Geophys. Res. Lett.* **27**, 1323–1326. (doi:10.1029/1999GL011070)
- Wu, P., Johnston, P. & Lambeck, K. 1999 Postglacial rebound and fault instability in Fennoscandia. *Geophys. J. Int.* **139**, 657–670. (doi:10.1046/j.1365-246x.1999.00963.x)
- Zemp, M., Haeblerli, W., Hoelzle, M. & Paul, F. 2006 Alpine glaciers to disappear within decades? *Geophys. Res. Lett.* **33**, L13504. (doi:10.1029/2006GL026319)
- Zhang, X., Zwiers, F. W., Hegerl, G. C., Lambert, F. H., Gillett, N. P., Solomon, S., Stott, P. A. & Nozawa, T. 2007 Detection of human influence on twentieth century precipitation trends. *Nature* **448**, 461–465. (doi:10.1038/nature06025)
- Zielinski, G., Mayewski, P., Meeker, L., Gronvold, K., Germani, M., Whitlow, S., Twickler, M. & Taylor, K. 1997 Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice cores. *J. Geophys. Res.* **102**, 26 625–26 640. (doi:10.1029/96JC03547)