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# Hazardous responses of the solid Earth to a changing climate

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## Summary

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Periods of exceptional climate change in Earth's 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 destabilisation. 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, whereas 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: (1) better understand those mechanisms by which contemporary climate change may drive hazardous geological and geomorphological activity; (2) delineate those parts of the world that are most susceptible; and (3) provide a more robust appreciation of potential impacts for society and infrastructure.

## Introduction

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Concern over anthropogenic climate change driving hazardous geological and geomorphological activity is justified on the basis of four lines of evidence: (1) periods of exceptional climate change in Earth's history are associated with a dynamic response from the geosphere; (2) 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 levels; (3) 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 (4) 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, although not exclusively, from the period following the end of the Last Glacial Maximum (LGM) around 20 ka BP (20 thousands of years before present). During the latest Pleistocene and the Holocene, the atmosphere and hydrosphere underwent dramatic transformations. Rapid planetary warming promoted a major reorganisation of the global water budget as continental ice sheets melted to replenish depleted ocean volumes, resulting in a cumulative sea-level rise of about 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 timescale, degree and rate of contemporary environmental change may result in a different hazardous 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.

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

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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 in 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 of either ice melt or increased precipitation levels. These environmental transformations in turn drive load pressure changes and increases in pore-water pressure which, 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 routinely 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; Hall, 1982; Wallmann 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; Luttrell & Sandwell, 2010; Wu et al., 1999; Wu & Johnston, 2000; Hetzel & Hampel, 2005) activity, marine (e.g. Maslin et al., 1998, 2004; Day et al., 1999, 2000; Masson et al., 2002; Keating & McGuire, 2004; McMurtry et al., 2004; Vanneste et al., 2006; Quidelleur et al., 2008; Lee, 2009; Tappin, 2010) and sub-aerial (Lateltin et al., 1997; Friele & Clague, 2004; Capra, 2006) landslides, tsunamis (McMurtry et al., 2004; Lee, 2009) and 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 destabilisation (e.g. Henriët & 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 significantly dependent on the scale and rate of future climate change. The scale of changes in key environmental conditions in post-glacial times was considerable, with the rapid loss of continental ice sheets after 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 approximately 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 a 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 about 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. Although the post-LGM climate of the latest Pleistocene and the Holocene was characterised by considerable variability (Mayewski et al., 2004), the transition from ‘ice-world’ to ‘water-world’ broadly altered the moisture balance in favour of a far greater incidence of warm and wet conditions, e.g. during the African Humid Period from about 14,800 to 5500 years 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, e.g. promoting landslide formation. Pratt et al. (2002), speculate that enhanced

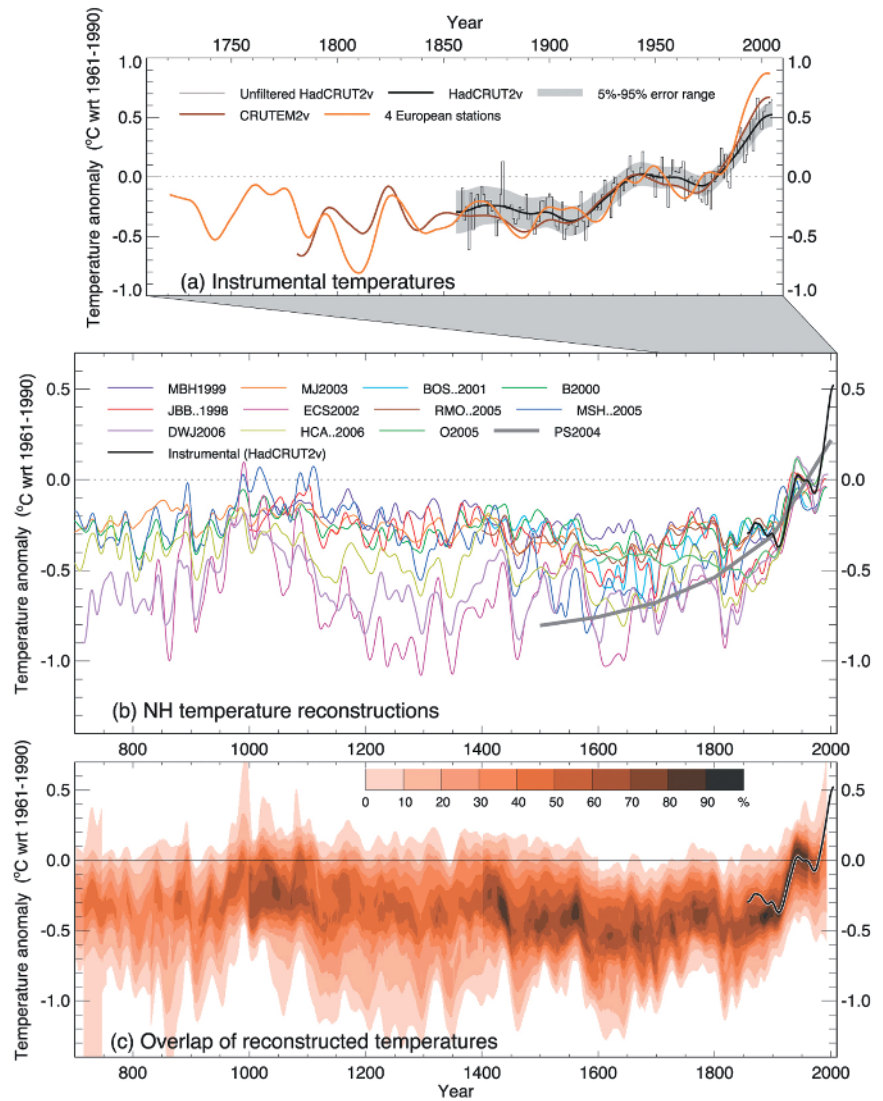
monsoon rainfall during the Early Holocene raised pore-water pressures in the Nepal Himalayas, resulting in an increase in landslide frequency. Similarly, Capra (2006) invokes more humid Holocene conditions to explain an apparent increase in the incidence of lateral collapse of volcanic edifices. In 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 ocean-loading due to rapid sea-level rise, but also elevated sediment pore pressures and gas hydrate destabilisation (see Lee, 2009 for more comprehensive discussion of these factors).

## Projected future climate changes and the potential for a geospheric response

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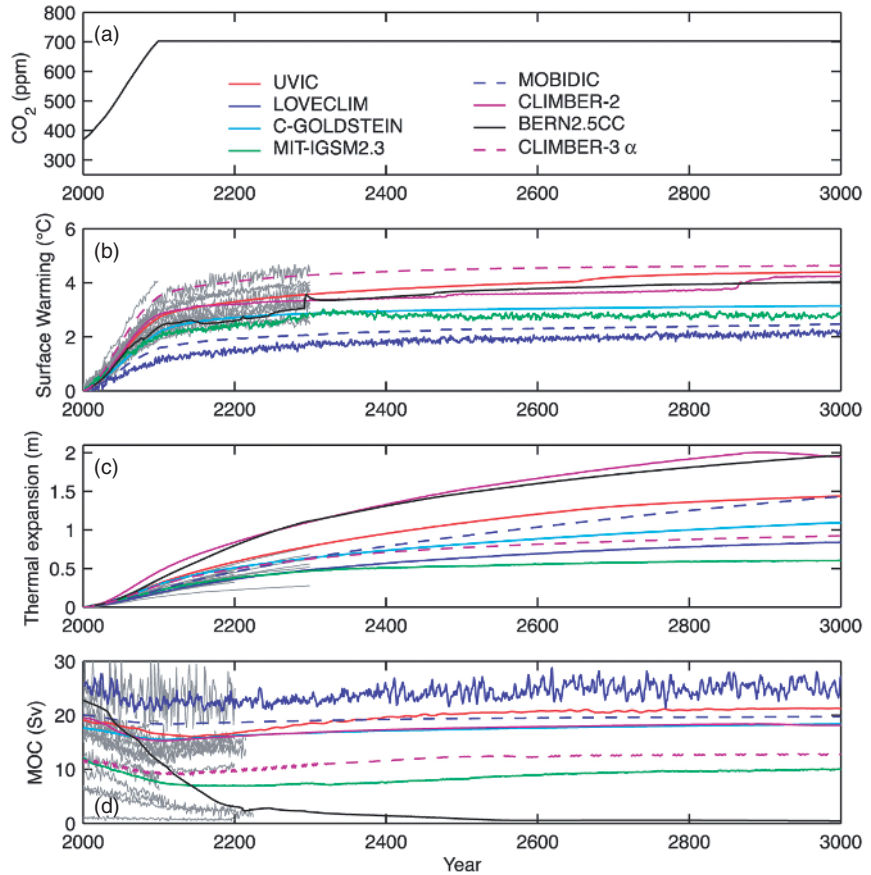
Since the LGM, about 20 ka BP, global average temperatures have risen by around 6°C, with a rise of close to 0.8°C occurring in the last 100 years (Figure 1.1). Without a major change in energy policy, GHG emissions are projected to rise substantially, increasing the global mean temperature by between 1.6°C 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 1.2). 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 realised. Considering that global GHG emissions are still on an upward trend, and with no binding agreement in place to reduce this, it is highly likely that warming will result in regional temperature rises of at least 2°C above the pre-industrial period. Under the high-end Intergovernmental Panel on Climate Change (IPCC) SRES (Special Report on Emissions Scenarios) emissions scenario (A1F1), Betts et al. (2011) 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 AR4 (IPCC 2007), if temperatures rise about 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 after 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°C 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., 2011).

**Figure 1.1** Records of Northern Hemisphere temperature variation during the last 1300 years. (a) Annual mean instrumental temperature records; (b) reconstructions using multiple climate proxy records; and (c) overlap of the published multi-decadal timescale 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 timescales <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 ( $^{\circ}\text{C}$ ) from the 1961 to 1990 mean. Reproduced from IPCC, 2007 Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon et al. Cambridge University Press, UK & USA. USA Figure 6.10 with permission.



Global temperature rises are driving increases in ocean volume due to thermal expansion of seawater and via melting of glaciers, ice caps, and the Greenland and West Antarctic ice sheets. Dependent on the scenario, annual thermosteric sea-level rise by 2100 could lie between  $1.9 \pm 1.0$  (B1 scenario) and  $3.8 \pm 1.3$  (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, whereas Pfeffer et al. (2008) estimate an upper bound of 2 m by 2100.

**Figure 1.2** Projected changes in (a) atmospheric CO<sub>2</sub>, (b) global mean surface warming, (c) sea-level rise from thermal expansion and (d) Atlantic Meridional Overturning Circulation (MOC) 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 stabilisation. Coloured lines are results from EMICs, grey lines indicate AOGCM results where available for comparison. Anomalies in (b) and (c) are given relative to the year (2000). Vertical bars indicate  $\pm 2$  standard deviation 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<sub>2</sub> greenhouse gases and the direct and indirect aerosol effects on radiative forcing differently. Despite similar atmospheric CO<sub>2</sub> concentrations, radiative forcing among EMICs can thus differ within the uncertainty ranges currently available for present-day radiative forcing. (Reproduced from 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. Solomon et al, Cambridge University Press, UK and USA. USA Figure 10.34.)



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% 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 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 disassociation.

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 hazardous 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  $\geq 0.5$  MPa (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- to 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 2.0 m rise of Pfeffer et al. (2008). Recently (1993–2003), annual sea level rise has been on the order of 2.4–3.8 mm/year (IPCC 2007), which translates broadly to an increased load pressure of 0.1 kPa every 3 years.

Although 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, increasing evidence supports the view that 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 1.1).

**Table 1.1** Examples of environmental drivers of seismicity, landslide slip and eruptive activity described in the literature, together with associated driving pressures

| Process   | Environmental driver                     | Driving pressures     | References                            |
|---|--|-----------------------|---------------------------------------|
| <i>Contemporary observations</i>                                |  |                       |                                       |
| Seismicity (south-east Germany)                                 | Precipitation                            | <1 kPa                | Hainzl et al. (2006)                  |
| Seismicity (San Andreas Fault, California)                      | Precipitation                            | About 2 kPa           | Christiansen et al. (2007)            |
| Seismic tremor/slow fault slip (Japan/Cascadia subduction zone) | Ocean loading                            | 15 kPa                | Rubinstein et al. (2008)              |
| Seismicity (Japan)  | Snow loading                             | 'A few kPa'           | Heki (2003)                           |
| Daily slip (Slumgullion landslide, Colorado)                    | Atmospheric pressure variation           | <1 kPa                | Schulz et al. (2009)                  |
| Eruptive activity (Pavlof, Alaska)                              | Ocean loading                            | 2 kPa                 | McNutt & Beavan (1987); McNutt (1999) |
| Seismicity  | Snow unloading and ground-water recharge | >5 kPa                | Christiansen et al. (2005)            |
| Seismicity (Juan de Fuca Ridge, Pacific North East)             | Ocean loading                            | 30–40 kPa             | Wilcock (2001)                        |
| Seismicity (East Pacific Rise)                                  | Ocean unloading                          | 1–2 kPa               | Guillas et al. (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)                      |

Pressure changes related to twentieth-century glacier ice-mass loss in Alaska and to future sea-level rise scenarios are included for comparison.

Based on observations of seismicity from south-east Germany, Hainzl et al. (2006) demonstrate that the crust can sometimes be so close to failure that even tiny (<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 either as a consequence of pore-pressure diffusion or crustal loading/unloading, and note that hydrologically induced stress perturbations of about 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 Helen's between 1989 and 1991 to slope instability or accelerated growth of cooling fractures within the lava dome after rainstorms, whereas 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 approximately 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. Schulz et al. (2009) show that diurnal tidal variations in atmospheric pressure amounting to <1 kPa modulate daily slip on the Slumgullion landslide in south-west 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 and Beavan (1987) and 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, whereas Christiansen et al. (2005) link shallow (<3 km) seasonal seismicity at large calderas and stratovolcanoes across the western USA with stress changes of >5 kPa associated with snow unloading and ground-water recharge. Guillas et al. (2010) argue for reduced sea level in the eastern Pacific before the development of El Niño conditions, and approximating to a 1- to 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. Although far from established, Podolskiy (2008) makes a case for an increase in global seismicity in recent decades, citing climate change as one potential driver.

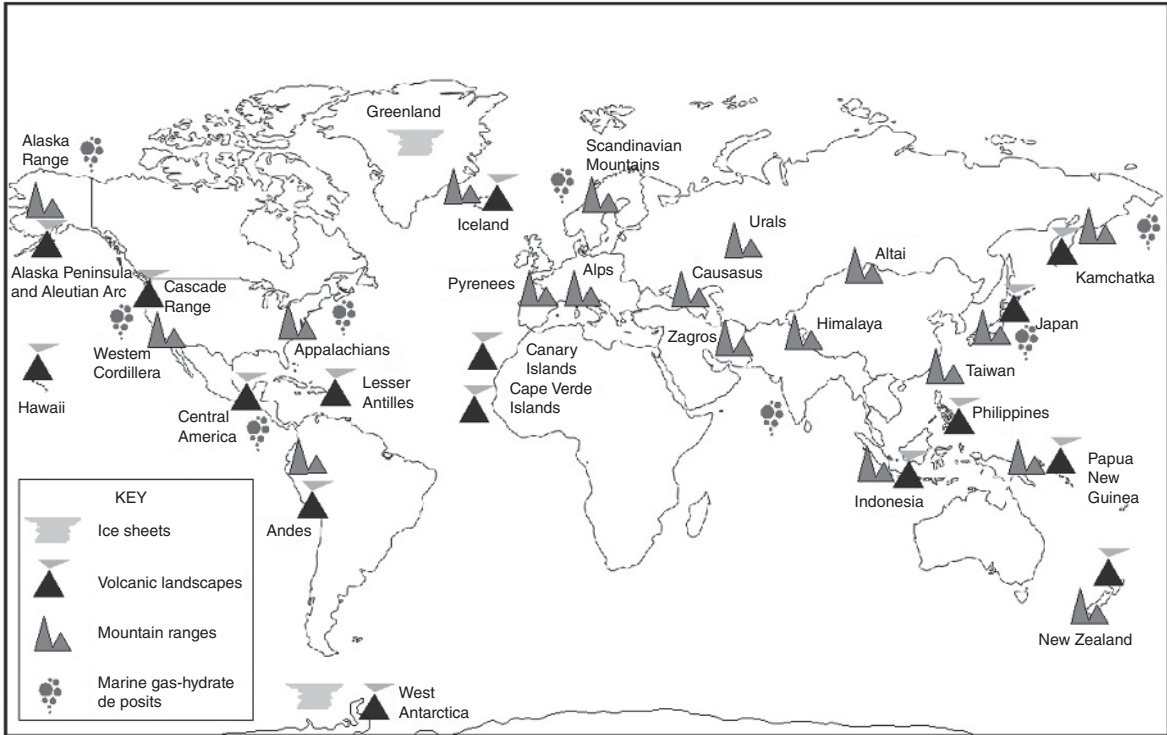
## Climate forcing of hazards in the geosphere

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 1.2 and Figure 1.3).

**Table 1.2** Potential geological and geomorphological hazards in the context of projected future climate changes

| Potential hazard                      | Mechanism/potential relationship with climate change  | Relevant climate drivers  | Environmental settings  | References  |
|---------------------------------------|---|---|---|---|
| Subaerial landslides and debris flows | Permafrost thaw; pore-water pressurisation; intense rainfall destabilising regolith   | Temperature rise; ice-mass loss; intense precipitation                        | Mountainous terrain; volcanic landscapes  | Deeming et al. (2010); Huggel et al. (2010); Keiler et al. (2010); Tuffen (2009)      |
| 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 et al. (2010); Tuffen (2009)   |
| 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 et al. (2010); Guillas et al. (2010)   |
| Volcanic activity                     | Unloading due to ice-sheet and glacier wastage; loading due to sea-level rise; pore-water pressurisation; intense rainfall destabilising regolith | Temperature rise; ice-mass loss; intense precipitation; ocean volume increase | Volcanic landscapes at all latitudes  | Deeming et al. (2010); Sigmundsson et al. (2010); Tuffen (2009)                       |
| Tsunamis                              | Submarine and sub-aerial 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 et al. (2010); Dunkley Jones et al. (2010); Tappin (2010) |

Columns show responsible mechanisms and relationship to climate change, relevant climate drivers, and most susceptible environmental settings.



**Figure 1.3** 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 summarised in Table 1.2.

### *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

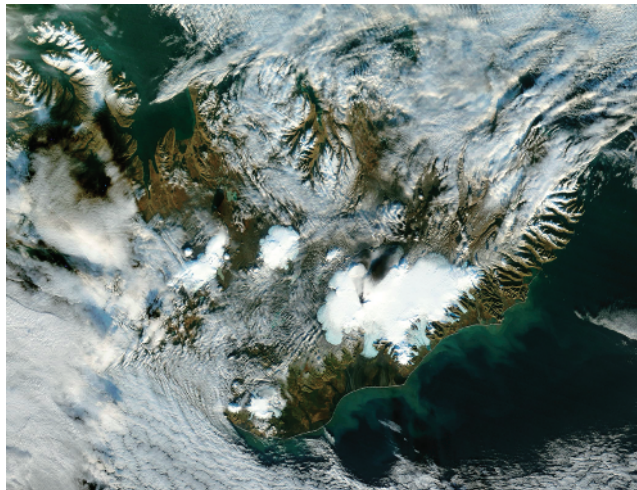
with isostatic rebound of the crust (e.g. Wu, 1999; Wu et al., 1999; Muir-Wood, 2000). For a 1-km ice load, the rebound may have totalled hundred of metres, with associated stresses totalling several megapascals, comparable with plate-driving stresses (Stewart et al., 2000). Ice thicknesses at Greenland and Antarctica currently exceed 3 km, providing potential for an ultimate rebound of more than 1 km should all the ice melt. Although 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 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 the 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, best known of which is the Storegga Slide, formed off the coast of Norway  $8100 \pm 250$  years BP (Lee, 2009; Tappin 2010). With a volume of between 2500 and 3500 km<sup>3</sup>, 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 north-east Scotland (Bondevik et al., 2005). A range of mechanisms capable of being driven by anthropogenic climate change is presented by Tappin (2010) as having the potential to trigger 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 about 8000 km<sup>2</sup>) (Figure 1.4) in Iceland presents the greatest threat

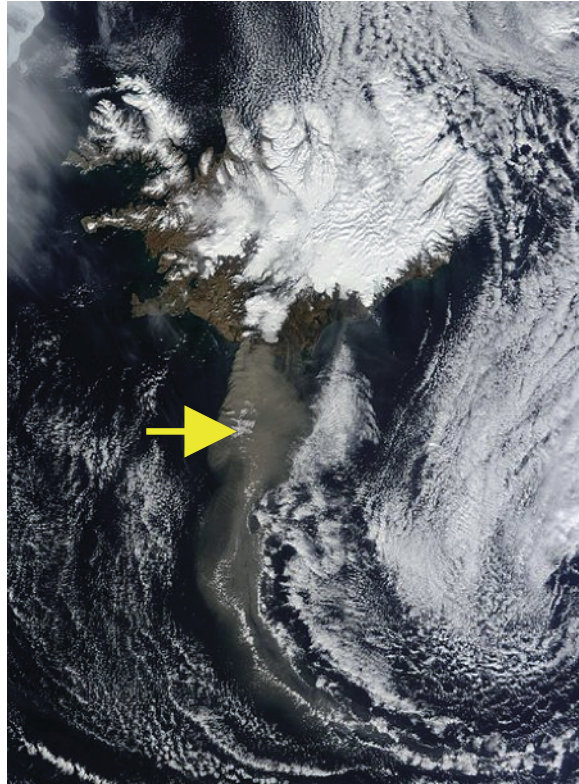
**Figure 1.4** Iceland's Vatnajökull ice cap captured by the moderate resolution imaging spectroradiometer (MODIS) on the Terra satellite in November 2004. Pagli and Sigmundsson (2008) predict that reduced ice load due to future climate change will result in an additional  $1.4\text{ km}^3$  of melt being produced in the underlying mantle every century – comparable to an eruption equivalent in size to the 1996 Gjálp eruption beneath Vatnajökull, every 30 years. (Reproduced courtesy of NASA.)



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 about  $0.5\text{ m/year}$ , and lost about  $435\text{ km}^3$  between 1890 and 2003 – about 10% of the total volume. In post-glacial times, the reduction in vertical load associated with an annual ice-thinning rate of about 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 and 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 support a more measured reaction from the crust and mantle to contemporary warming. Nevertheless, Pagli and Sigmundsson (2008) predict, on the basis of finite-element modelling, that the reduced ice load will result in an additional  $1.4\text{ km}^3$  of melt being produced in the underlying mantle every century – comparable to an eruption equivalent in size to the 1996 Gjálp 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 north west 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 (north-west USA).

Although the direct effects of increased levels of volcanic eruptions in Iceland may impinge on 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 south-eastwards over Europe. This resulted in extremely poor

**Figure 1.5** The ash plume from Iceland's erupting Eyjafjallajökull volcano on 19 April 2010. Ash in the atmosphere during April and May 2010 resulted in major disruption to air traffic across the UK and Europe. Any future rise in eruptive activity due to the loss of the Vatnajökull ice cap has the potential to cause comparable problems. (Reproduced courtesy of NASA.)



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 6 months; a similar event today would have the potential to cause major disruption to the north polar air transport routes. In this respect, and given the severe impact of the 2010 Eyjafjallajökull eruption (Figure 1.5) on air traffic across the UK and Europe, any potential increase in volcanic activity in Iceland would clearly be unwelcome. The future picture may not, however, be all bad. Sigmundsson et al. (in Chapter 5 of this book), for example, propose that a proportion of the new magma arising from future ice mass loss across Iceland will be 'captured' within the crust rather than erupted at the surface. For the Katla volcano, the recent unrest of which has raised concerns over another Icelandic eruption with air-traffic disrupting potential, such behaviour might actually work to reduce the likelihood of eruption.

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, which 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 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. 2011), 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. In addition, 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 destabilisation and failure due to slow cracking, held to be a contributory factor in the formation of *stürtzstroms* (giant, rapidly moving landslides) (e.g. Kilburn & Petley, 2003).

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 rock and ice avalanches, with volumes in excess of 10<sup>6</sup> m<sup>3</sup> in Alaska. With atmospheric warming in the state occurring at a rate of 0.03–0.05°C per year (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 be expected to increase the incidence of instability development and large-scale mass movement across all regions of elevated terrain at high latitudes.

### *Ocean basins and margins*

Warmer oceans have the potential to influence the stability of gas hydrate deposits in marine sediments and, as a consequence, destabilise 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 sub-aerial, 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 papers 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 destabilisation, but also through triggering large submarine sediment slides which may in turn generate tsunamis. Gas hydrates are ice-like solids comprising a mixture of water and gas (normally methane), the stability of which is strongly dependent on pressure–temperature conditions. They may become disassociated 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 ranges from 1000 GtC to 3000 GtC (giga-tonnes 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. Although rising ocean temperatures will tend towards destabilising 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 disassociation is triggered on a large scale it may be that all or much of the methane released will not reach the atmosphere, because (1) thermal penetration of marine sediments to the gas–hydrate interface could be sufficiently tardy to allow a new equilibrium to become established without significant gas release and (2) a fraction of any gas released may be oxidised in the ocean.

Gas–hydrate disassociation 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 physicochemical properties of hydrates seems to indicate that they are not able to instantaneously dissociate. Lee (2009) points out that few studies demonstrate an unambiguous link between hydrate disassociation 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 (Wallmann et al., 1988; Nakada & Yokose, 1992) have demonstrated that sea-level changes, about 100 m, are capable of triggering or modulating volcanic and tectonic activity. More specifically, Luttrell and Sandwell (2010) have shown that lithospheric flexure due to ocean loading caused by post-glacial sea-level rise was sufficient to ‘unclamp’ coastal transform faults, such as the San Andreas (California, USA), north Anatolian (Turkey) and Alpine (South Island, New Zealand), thereby promoting failure through the reduction of normal stress. They also demonstrated that, for plate boundary faults at subduction zones, reduced sea levels favoured offshore fault rupture, whereas elevated sea levels promoted landward rupture at greater depths. In a similar vein, Brothers et al. (2011) implicate a combination of loading and pore-pressure increases, associated

with periodic Late Holocene flooding of southern California's Salton Sea by the Colorado River, in triggering earthquakes on the southern Andreas Fault. Quidel-leur 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 and Shaw (1995), which saw centennial global eustatic sea level rise rates of approximately 5 m. Perhaps most significantly, in relation to the impact of future sea-level rise on volcanic systems, McNutt and 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 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 depths of  $\leq 5$  km. The findings of McNutt and 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 timescales dependent on 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 in 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 is 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% form islands or are coastally located, whereas a further 38% are found within 250 km of a coastline. When or if rising sea levels will result in a recognisable signal in 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 and Beavan (1987) and McNutt (1999) for modulation of Pavlof's eruptive behaviour.

Nakada and Yokose (1992) have demonstrated theoretically that the large (approximately 100 m) sea-level changes associated with glaciation–deglaciation cycles, and resulting in cumulative ocean loading/unloading of about 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 just 15 kPa. Wilcock (2001) provides convincing evidence for micro-earthquakes on the Endeavour segment of the Juan de Fuca Ridge (Pacific North East) being triggered by the loading effect of ocean tides, which result in vertical stress variations of 30–40 kPa, whereas Guillas et al. (2010) propose that ocean load pressure fluctuations as small as a few kilopascals modulate microseismicity on the East Pacific Rise.

Provided that 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 a reduction in the frictional resistance to fault slip. This mechanism has long been recognised 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- to 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.

### *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. A primary driver is rising rock temperatures and permafrost thaw, the latter being a critical mechanism via which climate is able to control slope stability and natural hazard potential in mountainous terrain (Gruber & Haeberli, 2007). As described in 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 approximately  $50 \times 10^6 \text{ m}^3$  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 on to the Kolka glacier

**Figure 1.6** On 20 September 2002, collapse of part of the Dzhimarai-Khokh peak on to the Kolka Glacier 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. (Reproduced courtesy of NASA. Image by Robert Simmon and Jesse Allen, based on data from the NASA/GSFC/MITI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team and MODIS Science Team.)



in 2002 (Figure 1.6). The resulting ice and rock avalanche entrained almost the entire glacier, accumulating a total volume of  $100 \times 10^6 \text{ m}^3$  travelling at a velocity of up to 80 m/s (Huggel et al., 2005). The avalanche transformed into a debris flow at lower altitudes, which led to the deaths of more than 100 people. Huggel et al. (2008) speculate that warming permafrost may have been implicated in the failure process. During the 20<sup>th</sup> century, permafrost has warmed by between 0.5 and 0.8°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 destabilisation 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 mobilising rock and regoliths 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 floods in the European Alps in 2005 (Keiler et al., 2010). Chiarle et al. (2007) recognise three types of event that lead to debris flows in the Alps, but which have general application to their formation in mountainous regions: (1) intense and prolonged rainfall, leading to the saturation and failure of debris accumulations; (2) short-duration rainstorms capable of destabilising a glacier drainage system; and (3) 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% 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), whereas 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 were developed as a consequence of retreat of the Grubengletscher Glacier in Wallis Canton. One of these, drained catastrophically in 1968 and again in 1970, resulted 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 (Dussaillant et al. 2009). 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 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 destabilised. Failure may be promoted by strong ground motion associated with earthquakes, and such a mechanism has been proposed to explain a 2.5 km<sup>3</sup> 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<sup>3</sup>, and presents a catastrophic threat to communities downstream should the rock dam become breached.

### *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 deglaciation-related hazards encountered in mountainous terrains of non-volcanic origin. As addressed in detail in Tuffen (2009), 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 notable in Alaska, Kamchatka, the Andes, the Cascades and New Zealand, any unloading effect is, however, likely to be negligible. Tuffen (2009) observes that ice thinning of  $\geq 100$  m 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 (2009), this may arise due to debulking 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). Although 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 sub-tropics, which are already becoming wetter as a consequence of anthropogenic climate change (Zhang et al., 2006). Mobilisation 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 mobilised pyroclastic material derived from the Vesuvius and Campi Flegrei volcanic centres, leading to the formation of approximately 150 debris flows, which resulted in 160 fatalities and extensive damage to Sarno and neighbouring population centres (Bronzi & 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, first 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).

## Conclusions

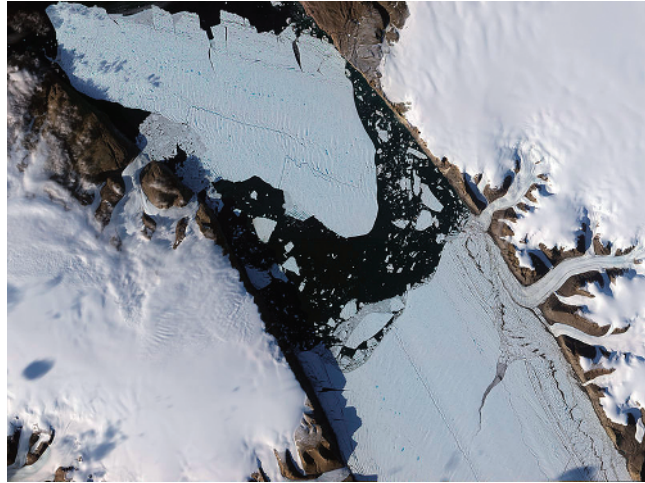
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Evidence from the study of periods of exceptional climate change, together with contemporary observations, support a robust link between changing climatic conditions and a broad portfolio of potentially hazardous geological and geomorphological processes. Modelling studies and the projection of current trends argue for elevated levels of a range of geological and geomorphological hazards in a warmer world, whereas 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 timescales 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 eliciting 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, Turpeinen et al. (2008) and Hampel et al. (2010) suggest that enhanced seismicity may be important on timescales as short as 10–100 years (Figure 1.7). A comparable timescale has been proposed (Gruber et al., 2004; Harris et al. 2009) in relation to the formation of large, deep-rooted, landslides after 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 non-linear 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: better understand those mechanisms by which contemporary climate change may drive hazardous geological and geomor-

**Figure 1.7** A 260 km<sup>2</sup> km fragment of Greenland's Petermann Glacier broke off in August 2010. Continued ice-mass wastage and consequent lithospheric rebound may ultimately result in an increase in seismic activity in the region.



phological activity; delineate those parts of the world that are most susceptible; and provide a more robust appreciation of potential impacts for society and infrastructure. More specifically, there is a need to (1) 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; (2) 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 (3) 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. For the first time, the IPCC explicitly addressed the impact of anthropogenic climate change on the geosphere, together with its manifold potentially hazardous consequences, in its 2011 report on climate change and extreme events (IPCC, 2011). It is strongly exhorted to continue to engage with the issue in future assessments and in particular in the IPCC's fifth assessment report, due to be published in 2013 and 2014. This seems to be particularly apposite given the outcome of the 2011 Durban climate conference, which effectively determined that little – if any – effective action to seriously curb global greenhouse gas emissions is likely before 2020.

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