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PREFACE

Climate forcing of geological and geomorphological hazards

The 12 research papers and two summaries of conference discussion sessions contained in this Theme Issue build upon presentations and dialogue at the Third Johnston–Lavis Colloquium held at University College London in September 2009. The meeting brought together delegates from the UK, Europe and the USA to address the issue of climate forcing of geological and geomorphological hazards, with a particular focus on examining the possibilities for a geospheric response to anthropogenic climate change. Papers included in this issue are a reflection of new research and critical reviews presented in sessions on: climates of the past and future; climate forcing of volcanism and volcanic activity; and climate as a driver of seismic, mass-movement and tsunami hazards. Two introductory papers set the scene. In the first, McGuire summarizes evidence for periods of exceptional past climate change eliciting a dynamic response from the Earth's crust, involving enhanced levels of potentially hazardous geological and geomorphological activity. The response, McGuire notes, is expressed through the triggering, adjustment or modulation of a range of crustal and surface processes, which include gas-hydrate destabilization, submarine and subaerial landslides, debris flows and glacial outburst floods, and volcanic and seismic activity. Adopting a uniformitarian approach, and acknowledging potential differences in both rate and scale from the period of post-glacial warming, McGuire goes on to examine potential influences of anthropogenic climate change in relation to an array of geological and geomorphological hazards across an assortment of environmental settings. In a second and complementary review paper, Liggins *et al.* evaluate climate change projections from both global and regional climate models in the context of geological and geomorphological hazards. The authors observe that, in assessing potential for a geospheric response, it seems prudent to consider that regional levels of warming at 2°C are unavoidable, with high-end projections associated with unmitigated emissions potentially leading to a global average temperature rise in excess of 4°C, and far greater warming in some regions. Importantly, they note that significant uncertainties exist, not only in relation to climate projections, but also with regards to links between climate change and geospheric responses. Using the format adopted by McGuire, Liggins *et al.* focus on high-latitude regions, global oceans, non-volcanic mountainous regions and volcanic landscapes.

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

The sensitivity to climate change of gas hydrates, in both marine and continental settings, has long captured interest, in relation to its potential role in past episodes of rapid warming, such as in the Palaeocene–Eocene thermal maximum (PETM), and in the context of anthropogenic warming. In the first of a pair of papers on the subject, Maslin *et al.* review the current state of the science as it relates to gas hydrates as a potential hazard. The authors note that gas hydrates may present a serious threat as the world warms, primarily through the release of large quantities of methane into the atmosphere, thus forcing accelerated warming, but also as a consequence of their possible role in promoting submarine slope failure and consequent tsunami generation. Maslin and colleagues also stress, however, that, while the destabilization of gas hydrates in permafrost terrains can be robustly linked to projected temperature increases at high latitudes, it remains to be determined whether or not future ocean warming will lead to significant methane release from marine hydrates. In a second paper, Dunkley Jones *et al.* look back to the PETM, the most prominent, transient, global warming event during the Cenozoic, in order to evaluate the effects of the rapid release of thousands of gigatonnes of greenhouse gases on the planet's climate, ocean–atmosphere chemistry and biota, for which the PETM perhaps provides the best available analogue. Dunkley Jones *et al.* support the view that, while gas-hydrate release was probably not responsible for an initial, rapid, CO_2-driven warming, the as yet unknown event responsible for this subsequently triggered the large-scale dissociation of gas hydrates, which contributed to further warming as a positive feedback mechanism. As the authors note, this somewhat equivocal situation ensures that the question of what role, if any, gas hydrates may play in anthropogenic warming remains to be answered.

Continuing the gas-hydrate theme, Day and Maslin summarize—at the end of this issue—a discussion session at the colloquium, on the theme of *Gas hydrates: a hazard for the 21st century?* While wide-ranging, discussion focused primarily on the distribution of the potential hazard and how the level of hazard might vary with climate change. The outcome of the session was a 'wish-list' that emphasized the need for, among other things, a better understanding of whether and how (immediately versus over a longer time-scale) 21st-century climate change will trigger hydrate release, and a more robust appreciation of the likely fate of released methane.

Looking forward, one of the potential hazards presented by gas hydrates is their possible role in the destabilization of submarine slopes. This is one theme addressed by Tappin within a broader review of submarine mass failures (SMFs) as tsunami sources that incorporates the climate dimension. Tappin highlights the importance of climate in 'preconditioning' sediment so as to promote instability and failure, including its influence on sediment type, deposition rate and post-depositional modification. The author also notes that climate may play a role in triggering SMFs via earthquake or cyclic loading associated with tides or storm waves. Tappin makes the important point that, in the past, climate influence on SMFs appears to have been greatest at high latitudes and associated with glaciation–deglaciation cycles, which had a significant influence on sedimentation, preconditioning and triggering. As a corollary, Tappin notes that, as the Earth warms, increased understanding of the influence of climate will help to underpin forecasting of tsunami-sourcing SMFs, in particular at high latitudes where climate change is occurring most rapidly.

The theme of slope destabilization and failure, this time in a subaerial setting, is continued in a paper by Huggel *et al.*, which examines recent large slope failures in the context of short-term, extreme warming events. Huggel and colleagues demonstrate a link between large slope failures in Alaska, New Zealand and the European Alps, and preceding, anomalously warm episodes. The authors present evidence supporting the view that triggering of large slope failures in temperature-sensitive high mountains is primarily a function of reduced slope strength due to increased production of meltwater from snow and ice and from rapid thaw processes. Looking ahead, they expect more frequent episodes of extreme temperature to result in a rise in the number of large slope failures in elevated terrain and warn of potentially serious consequences for mountain communities.

The slope failure hazard in mountainous terrain is also addressed by Keiler *et al.* in a paper that examines the influence of contemporary climate change on a broad spectrum of geomorphological hazards in the eastern European Alps, including landslides, rock falls, debris flows, avalanches and floods. In the context of the pan-continental 2003 heat wave and the 2005 central European floods, the authors demonstrate how physical processes and human activity are linked in climatically sensitive alpine regions that are prone to the effects of anthropogenic climate change. Importantly, Keiler *et al.* note that, while the European Alps, alongside other glaciated mountain ranges, are being disproportionately impacted upon by climate change, this is further exacerbated by regional factors, including local climatology and long-term decay of glaciers and permafrost. The authors conclude that future climate changes are likely to drive rises in the incidence of mountain hazards and, consequently, increase their impact on Alpine communities.

There is strong evidence for a crustal response to the rapidly changing post-glacial climate being elicited by load changes, either as a consequence of unloading at high latitudes and high altitudes due to ice-mass wastage, or as a result of the loading of ocean basins and continental margins in response to a 100 m or more rise in global sea level. The following three papers address the influence of load changes in the context of the triggering of seismicity and volcanism. In the first, Guillas *et al.* present the results of a statistical study of a putative correlation between contemporary variations in the El Niño–Southern Oscillation (ENSO) and the occurrence of earthquakes on the East Pacific Rise (EPR). The authors observe a significant (95% confidence interval) positive influence of the Southern Oscillation Index (SOI) on seismicity, and propose that increased seismicity on the EPR arises due to the reduced sea levels in the eastern Pacific that precede El Niño events, and which can be explained in terms of the reduction in ocean-bottom pressure over the EPR by a few kilopascals. Guillas *et al.* note that this provides an example of how variations in the atmosphere and hydrosphere can drive very small changes in environmental conditions that are able, in turn, to trigger a response from the Earth's crust. Most importantly, they speculate that, in a warmer world, comparable and larger changes associated with ocean loading due to global sea level rise, or unloading associated with the passage of more intense storms, may trigger more significant earthquake activity at submarine fault systems that are in a critical state.

Continuing the theme, Hampel *et al.* take a broader look at how faults have responded to variations in ice and water volumes as a consequence of past climate change. Using numerical models, the authors demonstrate that climate-driven changes in ice and water volume are able to affect the slip evolution of both thrust and normal faults, with—in general—both the slip rate and the seismicity of a fault increasing with unloading and decreasing with loading. Adopting a case-study approach, Hampel and colleagues provide evidence for a widespread, post-glacial, seismic response on faults located beneath decaying ice sheets or glacial lakes. Looking ahead, the authors point to the implications of their results for ice-mass loss at high latitudes, and speculate that shrinkage of the Greenland and Antarctic ice sheets as a consequence of anthropogenic warming could result in a rise in the frequency of earthquakes in these regions.

In a similar vein, Sigmundsson *et al.* evaluate the influence of climate-driven ice loading and unloading on volcanism, focusing on Iceland and, in particular, on the Vatnajökull ice cap. Noting that a significant pulse of volcanism in Iceland, at the end of the last glaciation, flags a link between unloading and volcanism, the authors model the effects of contemporary ice-mass loss at Vatnajökull on future magmatic activity. Using a viscoelastic model of glacio-isostatic adjustment that incorporates melt generation in the underlying mantle, Sigmundsson and co-authors predict that ice wastage will result in additional magma generation beneath Iceland. The authors expect more frequent or more voluminous volcanic activity to be a consequence of enhanced melt generation, but also observe that it could take longer than decades or centuries for the resulting magma to reach the surface. Sigmundsson *et al.* also show that ice unloading is likely to drive shallow magma reservoirs progressively towards failure, although this effect will be small and therefore contribute only to modulating 'normal' activity.

A more general evaluation of the impact of a changing climate on glaciated volcanoes is undertaken by Tuffen, who looks ahead to how the melting of ice caps on active volcanoes may influence volcanic hazards in the 21st century. In reviewing the evidence for current melting of ice increasing the frequency or size of future eruptions, Tuffen notes that much remains to be understood in relation to ice loss and increased eruptive activity. In particular, uncertainty surrounds the sensitivity of volcanoes to small changes in ice thickness and how rapidly volcanic systems respond to deglaciation. Nonetheless, Tuffen expects an increase in explosive eruptions at glaciated volcanoes that experience significant ice thinning, and increased frequency of lateral collapse at glaciated strato-volcanoes in response to anthropogenic warming. On the positive side, deglaciation may ultimately reduce the threat from volcanic debris flows (lahars) and meltwater floods from volcanoes that currently support ice caps.

Volcano lateral collapse in response to a changing climate is explored further in the final research paper by Deeming *et al.*, although in this case the driving force is precipitation rather than ice-mass loss. Deeming and co-workers present the results of a cosmic-ray exposure dating campaign at Mount Etna (Sicily), which constrains the timing and nature of collapse of the Valle del Bove, a major volcanic landslide scar on the eastern flank of the volcano. The authors link pluvial conditions during the early Holocene to the formation of a high-energy surface drainage system and to its truncation by a catastrophic lateral collapse event, *ca* 7.5 ka BP, which opened the Valle del Bove. A possible mechanism is proposed, whereby magma emplacement into a water-saturated edifice caused the thermal pressurization of pore water, leading to a reduction in sliding resistance and subsequent large-scale slope failure. Deeming *et al.* present the mechanism as one possible driver of future lateral collapse at ice-capped volcanoes and at those located in regions predicted to experience enhanced precipitation.

Concluding the volcanoes and climate change theme, Tuffen and Betts draw together the thoughts of delegates at a second colloquium discussion session, which focused on *Volcanism and climate: chicken and egg (or vice versa)?* Among other outcomes of the discussion came the feeling that the title of the session was too prescriptive, with perhaps 'Chicken and egg' being more appropriate. This, it was broadly felt, better reflected the complexities apparent in the volcano–climate system, within which both climate forcing of volcanism and volcanic forcing of climate appear to play a part. Going further, rather than a chicken and egg debate, it was suggested that it might be more beneficial to concentrate efforts on understanding better how the volcano–climate system evolves over time, responds to different forcings, and incorporates various feedback mechanisms. Among other proposals, it was advocated that climate models should incorporate variable volcanic inputs so as to better explore how volcanic activity might affect the climate in the future.

Together, this set of papers provides a coherent whole that addresses a wide range of issues relating to how climate change may force geological and geomorphological phenomena capable of acting to increase natural hazard risk in a warmer world. They reflect a field of research that is only now becoming recognized as important in the context of the likely impacts and implications of anthropogenic climate change. We hope that this Theme Issue will provide a marker that reinforces the idea that anthropogenic climate change does not simply involve the atmosphere and hydrosphere, but can also elicit a response from the Earth's crust and mantle. In this regard, we hope that it will encourage further research into those mechanisms by which climate change may drive potentially hazardous geological and geomorphological activity, and into the future ramifications for society and the economy.

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