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Climate change and geomorphological hazards in the eastern European Alps

BY MARGRETH KEILER1,†, JASPER KNIGHT2,* AND STEPHAN HARRISON2

1Department of Geography and Regional Research, University of Vienna, Universitätsstraße 7, 1010 Vienna, Austria
2Department of Geography, University of Exeter, Cornwall Campus, Penryn, TR10 9EZ, UK

Climate and environmental changes associated with anthropogenic global warming are being increasingly identified in the European Alps, as seen by changes in long-term high-alpine temperature, precipitation, glacier cover and permafrost. In turn, these changes impact on land-surface stability, and lead to increased frequency and magnitude of natural mountain hazards, including rock falls, debris flows, landslides, avalanches and floods. These hazards also impact on infrastructure, and socio-economic and cultural activities in mountain regions. This paper presents two case studies (2003 heatwave, 2005 floods) that demonstrate some of the interlinkages between physical processes and human activity in climatically sensitive alpine regions that are responding to ongoing climate change. Based on this evidence, we outline future implications of climate change on mountain environments and its impact on hazards and hazard management in paraglacial mountain systems.

Keywords: paraglacial; hazards; climate change; risk management

1. Introduction

Mountain systems are particularly sensitive to climate change because of climate amplification by feedback associated with high-elevation snowcover, albedo and heat budgets (Haeberli et al. 2007; Vavrus 2007). Temperature changes in the European Alps, for example, have increased twice as much as the global average since the late nineteenth century, and precipitation and other variables have also increased nonlinearly, with significant regional and seasonal differences, and differences by elevation and aspect (Auer et al. 2007; Haeberli et al. 2007; Brunetti et al. 2009). Regional changes in the distribution of both snow and rainfall have implications for snowcover thickness and duration (which also affect sub-surface temperatures), and catchment runoff (Beniston et al. 2003; Vanham et al. 2008). Temperature and precipitation changes can be demonstrably

*Author for correspondence (j.knight@exeter.ac.uk).
†Present address: Duke University, Division of Earth and Ocean Sciences, Durham, NC 27708, USA.

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linked to changes in glacier mass balance (including equilibrium line altitude) and terminus position, in particular at high elevations (Zemp et al. 2006; Lambrecht & Kuhn 2007; Huss et al. 2008; Steiner et al. 2008; Nemec et al. 2009). Permafrost monitoring sites throughout the Alps also show changes in alpine permafrost distribution, temperature profile and active-layer thickness (Harris et al. 2003). Events specifically related to variations in precipitation, such as snow avalanches and upland river floods, have also increased in frequency and magnitude in many areas (e.g. Beniston et al. 2003, 2007; Baggi & Schweizer 2009; Hilker et al. 2009).

While the direct effects of climate forcing on these cryospheric systems have now been monitored for several decades in the European Alps, the indirect effects on geomorphological processes and on sedimentary systems are less well known. Based on records of past events, alpine geomorphological hazards such as landslides, debris flows, mudflows and other expressions of slope instability can result from aspects of human activity and climate variability alone or in combination (e.g. Gehrig-Fasel et al. 2007; Stoffel et al. 2008). While human activity and land management are important, it is now being acknowledged that ongoing climate change is exerting a more significant role in the generation of geomorphological hazards by influencing the operation of all landscape elements (e.g. Agrawala 2007; López-Moreno et al. 2008; Stoffel et al. 2008). Cryospheric responses to climate change in particular can give rise to ‘downstream’ geomorphological impacts such as hazard events that represent periods of decreased land-surface stability (Gude & Barsch 2005; Stoffel & Beniston 2006). Furthermore, geomorphological processes in high-relief areas are strongly influenced by slope angle and aspect, sediment availability and slope moisture supply, and these processes (and their capacity to lead to hazards) evolve in a downslope direction, leading to high spatial and temporal variability in process domain and thus hazard risk.

As a result, the dynamics of, and controls on, geomorphological hazards under the effects of ongoing climate change are presently a major issue for landscape management and planning in the European Alps and similar mountain settings worldwide (Agrawala 2007; López-Moreno et al. 2008), particularly in areas of high population density in alpine valleys. There is, therefore, an imperative for accurate monitoring and modelling of alpine geomorphological processes and hazard risk mapping in order to minimize potential impacts on human activity within sensitive alpine landscapes.

Future climate change can be predicted by global climate models (GCMs), but the downscaled results from different scenarios highlight regional uncertainty in these predictions (e.g. Wanner et al. 2006; Allan & Soden 2007; Reichler & Kim 2008). For the European Alps in particular, GCMs cannot account for the climatological effects of high relief owing to the coarse spatial resolution of the climate models and their insensitivity to sub-grid scale variability (Calanca et al. 2006). In addition, climate feedbacks are significant in mountain settings and have implications for local patterns of snow preservation and melt and maintenance of permafrost (Vavrus 2007; Slaymaker & Embleton-Hamann 2009). These are significant areas of concern that highlight the complexity of mountain landscape systems and their land-surface (geomorphological) responses to future climate change.
Aims and structure of this paper

This paper considers some of the impacts of future climate change on geomorphological processes and natural hazards in the eastern European Alps. These probable impacts are inferred based on observations of those geomorphological processes and natural hazards that took place during the 2003 heatwave and 2005 summer floods, both of which had impacts across the European Alps. These recent events are chosen because their processes and impacts were well monitored and because GCMs predict increased frequency of temperature and precipitation extremes over central Europe (Frei et al. 2005). This means that geomorphological responses to these recent events are likely to be indicative of wider landscape responses to be expected under future climate change.

In detail, the paper has three main aims: (i) to outline the present climatic regime of the European Alps and recent changes in glaciers, alpine permafrost and rivers, (ii) to describe the climate events and geomorphological impacts of the 2003 heatwave and 2005 floods, and (iii) to discuss these geomorphological impacts within the wider context of ongoing climate change within sensitive paraglacial alpine landscapes. This forward projection of probable impacts has important implications for planning, policy and management of sensitive alpine landscapes and environments.

Climate and environments of the eastern European Alps

The European Alps is a climatically transitional region, located at the interface between major atmospheric circulation source areas of the Atlantic Ocean, Mediterranean Sea and continental Europe west of the Urals. As such, there are major north–south and east–west climatic gradients (Auer et al. 2005). The European Alps are also split into eastern and western sectors by the Rhine and Splügen pass; the eastern sector, discussed in this paper, has Atlantic-influenced climate in its northern part, with a continental influence in the east and Mediterranean influence in the south (figure 1). Monitoring of temporal changes in temperature and precipitation patterns across the Alps has already highlighted the effects of ongoing climate changes on temperature and precipitation anomalies, winter snow depth and duration and river discharge (e.g. Auer et al. 2005). Therefore, future patterns of these meteorological phenomena will reflect synoptic-scale reorganization of atmospheric circulation cells and air mass source areas that are a probable outcome of anthropogenic global warming (Lionello et al. 2008).

In detail, precipitation varies markedly across the Alps by both yearly and seasonal totals, and in response to variations in moisture source, wind direction and microclimate (Frei & Schär 1998; Casty et al. 2005; North et al. 2007). Precipitation is highest on the northern side of the Alps, and decreases from west to east with distance from Atlantic source regions. Temperature variability across the Alps is mainly by elevation, with valley floors substantially warmer than adjacent mountain tops. Temperature inversions are common during winter (Agrawala 2007). Variation in alpine climate is also linked closely to the North Atlantic Oscillation, which in part determines
the trajectory of precipitation-bearing storm tracks across Europe, as well as temperature anomalies (Beniston & Jungo 2002; Casty et al. 2005; Bartolini et al. 2009).

The distribution and thickness of alpine permafrost closely follows these temperature and precipitation patterns (Harris et al. 2003; Lüetschg et al. 2008). On north-facing slopes, permafrost occurs at altitudes above 2600 m, on south-facing slopes above 3000 m, and in zones with long-lasting avalanche snow at altitudes several hundred metres lower (Haeberli 1975; Lieb 1998; Lüetschg et al. 2008). Permafrost is also sensitive to snowcover, topography, aspect and ground surface material (Damm 2007). Recent studies show ongoing permafrost warming in the European Alps: during the twentieth century, permafrost warmed by 0.5 to 0.8°C in the upper tens of metres (Gruber et al. 2004), particularly at higher elevations, with accompanying thickening of the seasonal active layer (Harris et al. 2003, 2009).

Recent climate-change effects are also recorded in alpine glaciers (Haeberli et al. 2007; Huss et al. 2008) which, by the 1970s, had lost 35 per cent of their 1850 value of total area, and almost 50 per cent by 2000 (Zemp et al. 2006). Across the Alps,
however, there is wide variability in glacier response, attributed to microclimate effects (Lambrecht & Kuhn 2007). Changes in snowmelt and glacier ablation have implications for the amount and timing of mountain-river discharge.

(a) Future climate patterns in the European Alps

Modelled predictions of future climate changes in the European Alps, including spatial and temporal patterns of temperature and precipitation anomalies relative to present conditions, have been undertaken on both continental and regional scales. Following Déqué et al. (2007), it is argued that the temperature in the European Alps will increase by 0.3 to 0.45°C per decade to 2100 from 1961 to 1990 mean values, with a higher expected increase in summer and autumn and increased frequency of summer heatwaves (Beniston 2004). This averaged value will be substantially modified, however, by altitudinal and other local effects. Changes in precipitation in Europe will result in a higher north–south gradient, with increased precipitation in the north (especially in winter) and a strong decrease in the south (especially in summer). In the Eastern Alps, winter precipitation is expected to increase in the northwest and decrease in the south and east, with increased precipitation intensity in all regions (Frei et al. 2005). Despite uncertainties related to regional climate simulations of precipitation in complex terrain, Beniston (2006) suggested that mean and extreme precipitation values may undergo a seasonal shift, with more spring and autumn heavy precipitation events than at present, and fewer in summer.

Snow is a key feature of environmental change in alpine areas (Laternser & Schneebeli 2003; Vavrus 2007). Under current climatic conditions, a shift in snow amount and snowcover duration can already be observed (Laternser & Schneebeli 2003). Owing to warmer temperatures in the next decades, the snow volume may respond with reduction at mid-elevation sites (1000–2000 m) by 90–50 per cent and at high-elevation sites by 35 per cent (Beniston et al. 2003). Furthermore, the duration of snowcover will be sharply reduced, mainly because of earlier spring snowmelt (Beniston et al. 2003; Laternser & Schneebeli 2003). Changes in snowcover thickness and duration also affect sub-surface temperatures and permafrost distribution (Gruber et al. 2004; Harris et al. 2009); therefore decreasing snowfall will promote permafrost degradation, irrespective of changes in air temperature.

Modelled changes in glacier volume and extent show a clear relationship to increasing temperature. Warming of 3°C in summer air temperature would reduce current Alpine glacier cover by some 80 per cent (Zemp et al. 2006). In the event of a 5°C temperature increase, the Alps would become almost completely ice free. The impacts of precipitation changes are deduced with less certainty because of its covariation with temperature and role of seasonality (Zemp et al. 2006; Steiner et al. 2008). In addition, glacier decay also leads to climate feedback through changes in surface albedo, areal downwasting and stagnation, and formation of debris-covered glacier margins (Paul et al. 2004; Kellerer-Pirklbauer et al. 2008).

In order to investigate the probable impacts and interlinkages between climate forcing and geomorphological responses in the eastern European Alps, we present two case studies of recent climatological events: the 2003 heatwave and 2005 floods.

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(b) The 2003 heatwave and its impacts

The summer of 2003 was characterized by the hottest temperatures in the last 500 years in Central Europe (Luterbacher et al. 2004) and the warmest summer in a 1250 year long record for the European Alps (Büntgen et al. 2006). The mean summer temperatures (June–August) in a large area of the European Alps exceeded the 1961–1990 mean by 3–5°C, and showed high spatial anomalies (Schär et al. 2004). At the Hoher Sonnblick observatory (3106 m above sea level (a.s.l.)), located in the central Austrian Alps, a mean air temperature of 4.7°C was recorded during summer 2003, which is 4.4 times the standard deviation of the long-term mean (1886–2000; Koboltschnig et al. 2009). Summer precipitation in Austria and Switzerland was only 50 per cent of average (Patzelt 2004; Schmidli & Frei 2005), which had also been preceded by a dry spring (February–June). This situation was similar across Europe (Schär & Jendritzky 2004). The extreme temperature and precipitation conditions corresponded to persistent anticyclonic conditions during May–August 2003 (Black et al. 2004), which reinforced dry soil conditions (Fischer et al. 2007; Fennessy & Kinter 2009). Rapid glacier mass loss and ice-margin retreat associated with the 2003 heatwave also changed river discharge and initiated mass-movement events in the surrounding mountains during this period and afterwards.

The summer 2003 heatwave triggered a record Alpine glacier loss that was three times above the 1980–2000 average (Haeberli et al. 2007), continuing a long-term and accelerating pattern of mass loss (Zemp et al. 2006). Main factors for this remarkable 2003 loss were a smaller snowpack owing to the low springtime precipitation, and melting of firn in the accumulation area of small- and medium-sized glaciers, resulting in an albedo feedback with long-term effects. After the melt of the spring snowcover, the bare glacier surface had a lower albedo, which was additionally decreased owing to deposition of dark, wind-blown dust during the dry summer (Paul et al. 2005; Haeberli et al. 2007; Koboltschnig et al. 2009). In 2003, Austrian glaciers (88 measured) retreated by an average of 23 m and with a maximum distance of 73 m (Patzelt 2004), exposing large, debris-covered areas. According to the long-term glacier mass balance time series (e.g. Vernagtferner in Austria from 1965 to present) the mass balance of 2002/2003 was the most negative on record (CFG 2009).

The response of permafrost temperature and the thickness of the active layer varied considerably in summer 2003 (Harris et al. 2009). In 2003, the active layer of ice-rich frozen debris at Murtèl-Corvatsch in the Swiss Alps was deeper than previously recorded, but the effects of the higher temperature were restricted by greater latent-heat demands (Harris et al. 2009). In contrast, the thaw depth in permafrost on bedrock slopes was twice the average of previous years and indicates a strong coupling between atmospheric and ground temperatures (Gruber et al. 2004). Permafrost degradation set into action by this warming was reflected in increased rock-fall activity throughout the Alps during summer 2003 (Gruber et al. 2004; Fischer et al. 2006). The response of permafrost to the atmospheric warming generally takes place at different scales of time and depth. In particular, localities near the lower elevational limit of the discontinuous permafrost are very sensitive to changes, and respond with a short time lag (of days–months). For example, a large rock-fall event at the elevation of the lower permafrost boundary on the Matterhorn (Switzerland),

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July 2003, revealed weakened interstitial ice at the back of the rock-fall scar (Nötzli et al. 2004). Large-scale responses to warming permafrost, such as deep-seated slope instabilities, may show a delay of decades or centuries (Gruber et al. 2004; Harris et al. 2009).

Further effects of the 2003 heatwave are complex hydrological responses of rivers, both within alpine basins and also in their lower catchments (Zappa & Kan 2007). Apart from the physical characteristics of the basins, runoff is also influenced by anomalies in air temperature, potential evapotranspiration, snow accumulation and ice melt (Zappa & Kan 2007). Meltwater runoff is a function of the degree of glacierization of the basin; a historical minimum of summer discharge results from glacierization of less than 1 per cent of basin area, whereas in basins of up to 10 per cent glacierization, summer discharge was about 70–80 per cent of average (Zappa & Kan 2007). Koboltschnig et al. (2009) presented similar results from the glacierized Goldbergkees basin in the Austrian Alps, where glacier melt during August 2003 contributed 81 per cent of total runoff. Only in basins where glaciers covered more than 15 per cent of basin area did increased glacier melt compensate for reduced runoff in ice-free areas of the basin. In 2003, runoff yield in such heavily glaciated basins was close to summer and annual averages, but sub-basins exhibited strong positive and negative runoff anomalies (Koboltschnig et al. 2009; figure 2).

The impacts of the 2003 heatwave on society are multi-faceted. The high temperature and drought conditions contributed directly to increased mortality by between 35000 (Schär & Jendritzky 2004; Fischer et al. 2007) and 70000
Figure 3. Map of 72 h total precipitation (in mm) from 21 to 24 August 2005 (starting with 06.00 UTC to 06.00 UTC) in the European Alps region (Frei 2006). Outline of Switzerland and Austria shown for scale and location.

(Gómez & Souissi 2008) across Europe; crop failure and sharply reduced animal fodder production; and forest fires. The strongly reduced discharge in many rivers also affected downstream navigation and industry (Beniston 2004).

(c) The 2005 flood event and its impacts

In August 2005, Central Europe and especially the Alpine region was affected by severe floods accompanied by river-bank erosion and sediment transport, as well as debris flows, rock falls and landslides in the smaller catchments (Rickenmann et al. 2008). These events caused the most catastrophic flood damage in the last 100 years with respect to loss of life and damage to infrastructure, communication routes and agriculture (Beniston 2006; Frei 2006). In Switzerland, the August 2005 event caused one quarter of all damage by floods, debris flows, landslides and rock falls recorded since 1972 (Hilker et al. 2008).

The major factor for the occurrence of the flooding event was heavy precipitation on 20–23 August 2005. The most intense rainfall was located on the northern slopes of the Alpine ridge (figure 3), which was caused by Vb-type atmospheric patterns, similar to that which had caused previous flood events in Austria (Amt der Vorarlberger Landesregierung 2005). A low-pressure system situated over the Gulf of Genoa first brought heavy precipitation in the south and southeast of Austria, than moved slowly to the east and circled back to the Alps. The warm and moist air was lifted by both a cold air mass, located over Bavaria (southern Germany), and the topographic effect of the alpine ridge (Amt der Vorarlberger Landesregierung 2005).

Several factors apart from the high precipitation rate (30 h of rainfall with an intensity of more than 10 mm h$^{-1}$ for several hours) contributed to the high runoff in 2005: (i) intense rainfall occurred across a large area and covered whole catchments and valleys, (ii) the soil was already pre-saturated owing to a very wet situation in July and August, leading to rapid and high surface runoff, and (iii) because of high summer air temperatures, the freezing level was above...
Table 1. Discharge of 2005 flood peak and frequency of the event in selected catchments in the state of Tyrol, Austria (adapted from BMLFUW 2006a).

<table>
<thead>
<tr>
<th>catchment name</th>
<th>gauge location</th>
<th>catchment area (km²)</th>
<th>flood peak (m³ s⁻¹)</th>
<th>frequency (yr)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lech river</td>
<td>Steeg</td>
<td>247.9</td>
<td>361</td>
<td>~5000</td>
<td></td>
</tr>
<tr>
<td>Lech river</td>
<td>Lechaschau</td>
<td>1012.2</td>
<td>943</td>
<td>&gt;500</td>
<td></td>
</tr>
<tr>
<td>Rosanna river</td>
<td>St Anton</td>
<td>130.6</td>
<td>&gt;54</td>
<td>&gt;100</td>
<td>gauge destroyed 22 Aug 2005 (21.30 h)</td>
</tr>
<tr>
<td>Trisanna river</td>
<td>Galtür</td>
<td>97.6</td>
<td>&gt;141</td>
<td>~5000</td>
<td></td>
</tr>
<tr>
<td>Sanna river</td>
<td>Landeck</td>
<td>727.0</td>
<td>514</td>
<td>~5000</td>
<td></td>
</tr>
<tr>
<td>Inn river</td>
<td>Innsbruck</td>
<td>5792.0</td>
<td>1511</td>
<td>≥200</td>
<td></td>
</tr>
</tbody>
</table>

2900–3200 m a.s.l., so only a small amount of precipitation could be buffered as snow. In addition, glaciers were already saturated with meltwater owing to the high summer temperatures (BMLFUW 2006a).

In the eastern European Alps (Switzerland, western Austria (states of Vorarlberg and Tyrol) and southern Germany), this climatological situation resulted in large and long-lasting river discharges (see table 1 for the Tyrol). The high discharge was accompanied by intense sediment transport related to high erosion rates and subsequent sediment deposition mainly on floodplains. In smaller catchments, a high number of debris flow events occurred: in Austria alone, 115 debris flows and 111 other landslides were recorded (Internationale Forschungsgesellschaft Interpraevent 2009), mainly with medium to high sediment volumes. A few debris-flow events transported more than 100,000 m³ of sediment (Rickenmann et al. 2008). A substantial part of the sediment load (debris and woody debris) accumulated as torrent fans in the main valleys. Some of the debris flows delivered their sediment load into mountain rivers and contributed to the high sediment transport in the river downstream, in addition to the sediment produced locally (Rickenmann et al. 2008). The strong geomorphological activity during the flood event resulted in changes to channel courses, enhanced bank overtopping and sediment deposition outside the main channels. This led to substantial flood damage on inhabited areas and infrastructure along the river channels (BMLFUW 2006a,b; Rickenmann et al. 2008).

The municipality of Pfunds, in the Tyrol, was one of the communities heavily affected by the 2005 floods. Pfunds is located on the fan of the Stubenbach river, which is a left tributary of the Inn river with a catchment area of 30 km² between 525 m and 3035 m a.s.l. (figure 4). During the flood event, about 65,000 m³ of debris was deposited and reached up to 6 m deep (1 m on average). The debris was derived from sediments upstream and by partial erosion of the vegetation cover when reworking of the Pleistocene valley fill (BMLFUW 2006b). Therefore, it is assumed that the state of the catchment system changed owing to this extreme event and started to rework the sediments that were in quasi-storage within the upper catchment.

The Pfunds community consists of 2500 residents and 675 buildings. The 2005 event caused severe damage to those parts of the village located directly on the fan where 89 buildings were damaged or destroyed (figures 5 and 6). Losses for
Figure 4. Oblique Google Earth image (looking northwest) of the village of Pfunds and the high-relief catchment of the Stubenbach river.

Figure 5. View of debris accumulation on the Stubenbach fan during the 2005 flood event in the municipality of Pfunds. The grey circle shows the location of the building in figure 6 (photo: www.alpinesicherheit.com).

this community were estimated at 11 million Euro, including damage to buildings, roads, bridges and streets that were blocked for several days (BMLFUW 2006b). More widely, the 2005 event caused losses of up to 555 million Euro across Austria, of which 442 million Euro occurred in the western states of Austria (BMLFUW 2006b). Apart from the damage to buildings and industrial areas
owing to inundation, lateral erosion of the rivers and loose sediments caused the highest losses, including 100 days of discontinued service on the railway connecting Tyrol and Vorarlberg (the main line between Vienna and Zürich; Amt der Vorarlberger Landesregierung 2005; BMLFUW 2006b).

3. Discussion

The geomorphological events that took place in the eastern European Alps as a direct consequence of the 2003 heatwave and 2005 floods demonstrate the impact of meteorological variability in driving landscape-change processes over short time scales and in climatically sensitive regions, with wider impacts on ecosystems and human activity. There are four main points to be noted from these responses in the Alps.

— There is considerable spatial (and, lesserly, temporal) variation in river response to both flood and drought events, including where there is greatest sediment erosion, deposition and flood risk, both across the Alps as a whole and within individual catchments, including the transition from headwaters to immediately adjacent alpine valleys. Responses to the 2003 and 2005 events show this clearly, where floods had greatest geomorphic impact in upstream locations and droughts had greatest human impact in downstream locations. Antecedent conditions may be less important in flashy, upland catchments, but response is strongly modified by catchment relief and sediment availability that have potential to inhibit downstream water and sediment transport. Enhanced sediment evacuation from upland storage during the 2005 floods also reduced sediment yield subsequently.
In both events, glacier response was very rapid (such as high ice mass loss during the 2003 event), but this can be best described as a transient response superimposed on a longer time-scale climate-driven signal. Direct glacier response is measured by variations in meltwater production and mass balance, but other measures of glacier health, including position of the ice margin and structural integrity of the glacier as a whole (including presence of crevasses), should also be used. In addition, glacier responses to summer (temperature) and winter (precipitation, including snow) anomalies have their greatest and most immediate impacts on different parts of the glacier system, with high-elevation source areas more strongly precipitation limited, and lower ablation areas more temperature limited. Rapid temperature-driven retreat of the ice margin can also be followed, counter-intuitively, by glacier thickening and positive mass balance. Simple climatic forcing by temperature or precipitation alone, therefore, does not fully explain glacier dynamics.

Responses of alpine permafrost are difficult to quantify over short time scales because of, first, time-lag effects owing to the slow penetration into the sediment pile of the effects of climate forcing at the surface, and, second, the meteorological events that take place over short (sub-seasonal) time scales do not necessarily affect the following freezing/thawing season. This is clearly shown by responses to, in particular, the 2003 event (Harris et al. 2009). In addition, the role of permafrost is uncertain: permafrost monitoring stations are generally widely spaced and local effects of sediment type, microtopography and microclimate are probably significant processes that cannot be resolved spatially by the current monitoring stations. While the effects of land-surface heating can be effectively modelled, the role of increased surface wetness on permafrost stability is less well known, but may also include increased ice-lens thickness.

Implications for, and interactions between, these geomorphological processes and the biosphere are not well understood, and although individual events such as the 2003 and 2005 events do not have the temporal extent to trigger large-scale biosphere impacts, they form part of a long-term response to ongoing change. Biosphere effects are of particular importance for aspects of rock surface weathering and stability of vegetated slopes, and have long-term implications for ecosystem viability, including alpine refugia. Such biosphere responses may buffer effects of climate forcing of geomorphological hazards on warming mountain slopes.

Increased hazard frequency associated with both the 2003 and 2005 events impacted negatively on human activity, in both direct and indirect ways. These different responses are highly variable spatially and temporally, and in high-relief areas are also dependent on elevation and aspect. The geomorphological and wider landscape impacts of the 2003 and 2005 events can be considered analogous to the probable hazardous impacts of future climate changes in the eastern European Alps, under which meteorological variability will be more common (Beniston 2006; Rebetez et al. 2008). In turn, this has implications for risk management in the Alps.
Implication for natural hazard and risk management

Geomorphological events become natural hazards when they conflict with the human environment and lead to damage. The countries in the eastern European Alps have a long tradition in hazard mitigation, but climate and socio-economic change are major future challenges. Population and socio-economic trends in the eastern European Alps in the recent century (Bätzing 2003; Slaymaker & Embleton-Hamann 2009) reflect a shift from agriculture to service and leisure-oriented industries (Bätzing 1993; Keiler 2004). This trend is also observed in the development of tourist infrastructure in hazard-prone sites (Fuchs & Bründl 2005; Keiler et al. 2005), which can result in high and increasing losses if extreme events occur, as illustrated by the 2005 floods, and as has happened in the Alps during recent decades (e.g. avalanche events in 1999 (SLF 2000); flood events in 2002 (Hilker et al. 2009)). In contrast, the short-term impact and economic damage of the 2003 event in the European Alps was relatively low (Nötzli et al. 2004).

As highlighted above, geomorphologic responses to climate change are complex and highly variable spatially and temporally, but will have hazard-specific implications for risk management. The observed increase in periglacial and glacial hazards, as during the 2003 event, is concentrated in high-altitude areas where it impacts on small settlements and mountaineering/skiing infrastructure (paths, huts). This may be of limited economic significance nationally, but is important locally (Agrawala 2007). Public awareness of these mountain hazards (as opposed to floods and snow avalanches) is generally low, and hazard management has often focused on build-up of mountain monitoring systems (Kääb 2008). Despite this low direct effect on society, these high-mountain hazards increase the availability of easily mobilized debris and so increase future hazard risk. The 2005 event showed the connectivity between process chains or cascades resulting from such mountain-hazard events, which lead in turn to high sediment transport through landslides and other processes, and their impacts on valley settlements.

The traditional hazard assessment includes determining the hazard potential and its probability of occurrence by studying historical events, modelling and assessing individual processes and defined design events. The considered design events, which are the basis for delimitation of hazard zones and mitigation strategies, vary across the Alps. For example, Austria uses design events with a 100 year recurrence interval for floods and 150 years for debris flows. With reference to table 1, the 2005 event was far beyond these design events and therefore historical experience, meaning that the record of past events is no longer sufficient for hazard assessment. This reflects changes in the spatial pattern of climatic parameters, as well as the connectivity between different geomorphic processes that may alter magnitude–frequency relationships of hazards and damaging events. The role of climate change in the Alps, which the 2003 and 2005 events probably prefigure, has significant implications for hazard triggering and mitigation.

The model of risk management, conceptualized in terms of a ‘risk cycle’ (e.g. Carter 1991; Alexander 2000; Kienholz et al. 2004) with respect to natural hazards in the Alps), extends a traditional hazard-management framework that focuses on emergency management responses and procedures to hazardous events (figure 7). Consideration of these risks, including the use of mitigation

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measures and restrictions in land use, are part of an integrated risk-management approach with an ex ante and scenario perspective. This model integrates natural-science and social-science approaches with the aim of creating disaster-resilient communities through inductive learning (Fuchs 2009). Risk analysis and subsequent risk assessment are aimed at the evaluation and reduction of hazard risk, whereby prevention and mitigation are targeted at modification of the hazard or the modification of vulnerability of the human environment. This risk reduction includes prevention (monitoring and early warning, but also training and information) and mitigation (by protective measures and by risk transfer). Intervention in the risk cycle by event analysis, debrief and future risk-reduction strategies, referred to as follow-up works in figure 7, facilitate an enhanced future-risk analysis. The risk-cycle approach focuses on land-use regulation, risk transfer and information to the public to build up awareness (Holub & Fuchs 2009). Land-use planning activities, such as hazard maps, based on recurrence intervals, may change owing to variable climatic conditions. This sets in place a responsive framework, therefore, for the management of future changes in sensitive mountain environments as a result of climate change.

4. Conclusions and future outlook

The European Alps, in common with many mountains worldwide, are being disproportionately affected by ongoing climate change, which is, itself, superimposed upon a longer-term paraglacial signal that corresponds to processes

Figure 7. A ‘risk-cycle’ model of integrated risk management (adapted from Carter 1991; Alexander 2000; Kienholz et al. 2004).
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of landscape readjustment/relaxation (Church & Ryder 1972) following the last glacial event (the Würmian glaciation in the European Alps). Rock falls, landslides and debris flows are significant processes, while deglaciated slopes remain steep, unvegetated and water saturated (Stoffel et al. 2008). The frequency and magnitude of these events decrease exponentially over the paraglacial period, reaching background interglacial values up to 10,000 years following initial ice retreat (Ballantyne 2002).

A long-term consequence of paraglacial relaxation in mountains is that these locations can be considered as disturbed landscapes that are in transition from a glacial to a non-glacial state (Slaymaker 2009). Two important characteristics of this transition period are glacier retreat and melting of alpine permafrost, both of which are known from field studies across the European Alps and show consistent warming patterns over several decades (Harris et al. 2009). Ice retreat and increased active-layer thickness in higher-elevation settings are genetically associated with land-surface instability and enhanced sediment delivery to mountain slopes and valley bottoms. As such, it can be anticipated that ongoing and accelerating ice loss in the European Alps, over the next decades–centuries as a result of global warming, will have significant impacts on hazard type, location and frequency (Knight & Harrison 2009). Furthermore, increased sediment supply to mountain valleys will in turn result in future floodplain aggradation and increased flood hazards downstream, outside of the Alps region.

The European Alps is sensitive to such changes because (i) it is located at the boundary between different moisture source regions, (ii) its glaciers and permafrost are in long-term decay, and (iii) hazardous events can readily impact on areas of high population density in alpine valleys. Future climate changes in the Alps will probably have unforeseen outcomes on physical processes and natural hazards related to ongoing changes to the cryosphere caused by increasing temperatures (Knight & Harrison 2009). It is unlikely that coeval changes in precipitation alone can offset temperature-driven changes to alpine glaciers. Increased natural-hazard frequency and/or magnitude is a probable signature of climate forcing on unstable land surfaces. Understanding future climate impacts in these alpine areas, however, is hampered by problems of GCMs downscaling in areas of complex local relief, microclimate and sediment supply. Future research on geomorphic processes and monitoring of land-surface systems is needed to establish the sensitivity of these systems to climate forcing. Furthermore, this knowledge will lead to an improvement of hazard and risk management in the European Alps.

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References


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