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Detecting Potential Climate Signals in Large Slope Failures in Cold Mountain Regions

Christian Huggel, Simon Allen, John J. Clague, Luzia Fischer, Oliver Korup, and Demian Schneider

Abstract

Concern and interest are rising that climate change may have an adverse impact on slope stability in mountain regions. Rock slopes in high mountain areas with glaciers and permafrost are particularly sensitive to atmospheric warming. In fact, several large rock slope failures have been observed in high mountain areas around the world in recent years. However, the detection of changes in the frequency or magnitude of such slope failures is fraught with a number of difficulties and has only recently been addressed. Here we outline several approaches that could be used to detect a change in high mountain slope failure activity. Rather than present research results, we provide a conceptual design of how research in this field could be strengthened.

Keywords

Slope failure • Climate change • Detection and attribution

Introduction

Rock slope failures span a wide range of sizes from tens of cubic meters to many cubic kilometers. Depending on magnitude, location, fall or flow dynamics and runout, rock slope failures may pose significant hazards in mountain regions. Small- to medium-size slope failures ($<100{,}000$ m^3) commonly have small areas of impact but still can be destructive, for example where ski or other tourism infrastructure is affected. Large rock slope failures (up to tens of millions m^3) may evolve into rock avalanches with long runout distances (Legros 2002), and, consequently, more damage potential. In populated mountain valleys, towns may be impacted or even completely destroyed. Furthermore, process cascades can considerably increase the reach of damage, for example when a landslide enters high mountain lakes, triggering far-reaching lake outburst floods (Clague and Evans 2000).

Small rock slope failures have been regularly observed over historic time and are well known landslide processes to local residents and authorities. Large slope failures, however, are rare and generally are a poorly appreciated hazard. Due to their relatively low probability and large size, and related uncertainties over causes and triggers, large landslides pose challenges to researchers and to public authorities charged with managing associated hazards and risks.

In this context a fundamental problem that has arisen in recent years are potential changes in hazards due to (anthropogenic) climate change or other transient drivers. From a risk management perspective there are two aspects of concern: (1) robust detection of changes in mountain slope

C. Huggel (✉) • D. Schneider
Department of Geography, University of Zurich, Winterthurerstr. 190, Zurich CH-8057, Switzerland
e-mail: christian.hugggel@geo.uzh.ch

S. Allen
Climate and Environmental Physics, University of Bern, Bern, Switzerland

J.J. Clague
Department of Earth Sciences, Simon Fraser University, Vancouver, BC, Canada

L. Fischer
Geological Survey of Norway (NGU), Trondheim, Norway

O. Korup
Earth and Environmental Sciences, Potsdam University, Potsdam, Germany

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stability, both in the past and in the future, and (2) development of risk management strategies that adequately consider changes in hazards.

In climate sciences, as defined in the IPCC Assessment Reports, 'detection' is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change, whereas 'attribution' establishes the most likely causes for the detected change with some defined level of confidence (Hegerl et al. 2007). Research on detection and attribution is rooted in the field of physical climate sciences, but is now becoming increasingly important in impact studies as well (Rosenzweig et al. 2008). A recent IPCC report distinguishes different methods of attribution to climate change, including single-step and multi-step attribution that explicitly model the response of a system or variable to an external forcing and drivers, such as increased greenhouse gas emissions and related temperature increase (IPCC 2010). Single- and multi-step attribution studies of climate change impact are difficult to achieve due to incomplete understanding of how systems respond to climate change and the many confounding factors that complicate the response. Nevertheless, Pall et al. (2011) have recently successfully applied a multi-step approach for flood risks in the UK. More common in the field of climate change impacts is an associative pattern approach, where spatial patterns of observed impacts are compared with observed climate trends using statistics on large numbers of data series (Rosenzweig et al. 2008).

In the case of landslide research, detection and attribution to climate change is in its infancy. Reasons include a traditionally strong focus on geologic and geomorphologic aspects of landslides, lag effects with respect to contemporary climate change, and the general difficulty of detecting changes in landslide occurrence and its relation to climate change. Nevertheless, the response of alpine rock slopes to glacier downwasting has a longer history of scientific interest. It has been found that rock slope failure may result from slope steepening by glacial erosion and unloading or debuttressing due to glacier retreat (O'Connor and Costa 1993; Augustinus 1995). Ballantyne (2002) suggests that a rock slope may respond to glacier downwasting by failing in (1) large rock avalanches, (2) large-scale, progressive, yet slow rock mass deformation, and (3) frequent rock fall. Furthermore, it has been recognized that warming and thawing of permafrost can have an effect on the stability of steep rock slopes. Reduction of shear strength in ice-filled clefts due to thawing permafrost (Davies et al. 2001), water infiltration and advective heat transport processes in cleft systems (Gruber and Haeberli 2007), or thickening of the active layer (Gruber et al. 2004) are among the identified slope destabilization processes associated with climate change and permafrost. At shorter time scales, it has recently been demonstrated that particularly warm periods days and weeks prior to large slope failures likely affect slope stability (Huggel et al. 2010).

Here we present a conceptual model for five different approaches that can be used to rigorously detect changes in high-mountain rock slope failures in relation to climate change: (1) event inventories, (2) damage and loss data, (3) case studies, (4) causative and trigger factors, and (5) process models simulating climate change impact chains. The model provides a possible avenue for attribution studies. Each approach is briefly described, and existing studies reviewed to the degree they exist. Unfortunately, in many instances relevant studies applicable to high mountain slope failures do not exist. However, analogues from related research fields can be useful in providing guidance for future studies in high mountain environments.

Detection and Attribution Approaches

Slope Failure Inventories

Inventories of rock slope failures and other landslides provide data that are required to document change in the frequency or magnitude of events. Several difficulties have to be overcome, however, to detect any significant change over time. The source of documented events differs over long periods of time. Evidence of Holocene landslides generally derives from deposits identified in the field, whereas recent landslides, decades to centuries before present, can be documented from historic sources, media and scientific reports. The level of documentation has typically not been the same over the historic period; documentation becomes increasingly complete with time, which must be considered to avoid deriving erroneous trends. Small- and medium-size rock slope failures show a strong increasing trend of documentation for about the past two decades (Fischer et al. subm.).

A reasonable approach to avoid this documentation bias is to focus on large ($>100{,}000\ \mathrm{m}^3$) slope failures that can be assumed to be documented with higher consistency over the past 100 years in populated mountain regions such as the Alps in Europe. Alternatively, in remote mountain regions, archived aerial and satellite imagery can be used to retrospectively observe and map larger slope failure deposits (e.g., Allen et al. 2011). Geertsema et al. (2006) for instance analyzed 38 large landslides in rock and soil and found an increase from 1.3 to 2.3 landslides per year over 30 years, although the relation to potential effects of climate change over that period has not yet been clarified. There has also been a strong increase in the number of rock slope failures from glacial and periglacial areas in the Swiss Alps and

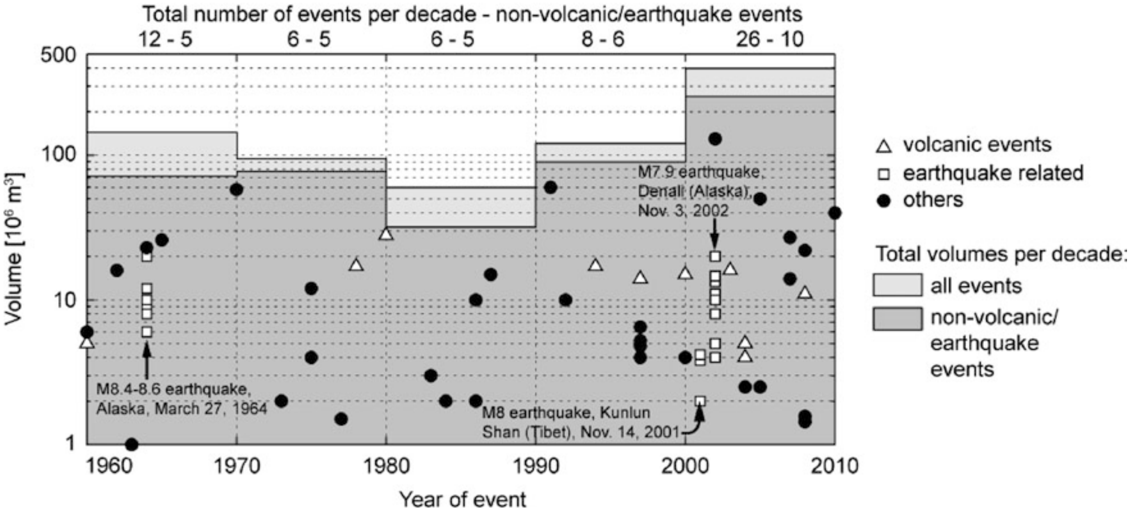

Fig. 1 Temporal distribution of worldwide large ($> 1 \times 10^6$ m^3) rapid mass movements in glacial environments. Events on volcanoes and related to seismic activity are marked. Note that the data can be biased due to non-uniform documentation throughout the past decades on a global scale

adjacent areas over the past two to three decades as compared to the rest of the twentieth century (Fischer et al. subm.). The trend hold true when only large events are considered although the sample then is reduced to about 20 events only. Interestingly, there is a second peak of increased rock slope failures around the 1940s that coincides with a warm period in the Alps.

Such regional-scale inventories include slope failures with a variety of different geology, topography, local climate and other factors that are known to influence slope instability. Local-scale studies are therefore important since to isolate the effects of these factors. Ravanel and Deline (2011) analyzed rock slope failures over the past ~150 years on high-mountain walls in the Mont Blanc area and found trends that are consistent with regional-scale studies: a large increase in slope failure activity during the past two to three decades and a second minor peak around the 1940s. The increase in event frequency during the past two decades as compared to the past 150 years is evident over the full range of magnitude (Ravanel and Deline 2011).

Figure 1 shows a global-scale inventory of 59 large ($>$ 1 million m^3) rapid mass movements in glacial environments between 1960 and 2010 based on Schneider et al. (2011). Both, number of events and volume, are significantly higher between 2000 and 2010 than in previous decades which would be consistent with the aforementioned findings at the regional- and local-scale (Fischer et al. subm., and Ravanel and Deline 2011, respectively). However, even though only large events are included here, it is not clear whether at the global scale any documentation bias can be excluded over the past 50 years. Furthermore, slope failures triggered by earthquakes and in volcanic environments have to be distinguished. In principle, climate change effects could lower the strength of rock slopes and thus make them prone to failure to lower-magnitude earthquakes, thus increasing the event frequency. However, we have no data that could provide corresponding evidence. Yet, it is interesting to note that even when subtracting seismically and volcanically related events, the increase in total failure volume over the past three decades holds true (Fig. 1). Overall, this analysis underlines that care is required when trying to extract potential climate signals based on slope failure inventories.

Inventories of high-mountain rock slope failures generally contain a limited number of events, typically $<$100 over the past ~100 years. Rigorous statistical analysis is therefore limited. Larger inventories of several hundred landslides (e.g. Korup et al. 2007; Guzzetti et al. 2009) offer opportunities for more sophisticated analysis. To test whether changes in boundary conditions such as climate change are detectable in landslide frequency-magnitude relationships, Huggel et al. (2013) created 100 random inventories, each containing 10,000 landslide events. They concluded that frequency-magnitude distributions are likely not adequate to detect potential changes in triggering conditions due to climate. For example, frequency-magnitude scaling statistics may render even a twofold increase of slope failure volume due to enhanced landsliding undetectable.

Damage and Loss Data

Data on damage and loss from natural hazards is systematically collected on national, regional/continental and global scales by a number of international, governmental and private companies, in particular the insurance sector (e.g. MunichRe 2008). Durham University maintains a global catalogue of fatal landslides (Durham Fatal Landslide Database; Petley et al. 2005). A number of landslide catalogues that provide information on damage and loss also exist at the national level, for instance in Italy (Guzzetti 2000). Based on the Durham landslide database, Petley (2010) documented an increase in landslide casualties or losses in south, east and south-east Asia between 2003 and 2009. Landslides in these regions are predominantly triggered by monsoon and tropical cyclone activity, but Petley (2010) attributed the increasing trend to changes in exposure, i.e. population growth, and not to climate change.

Over the past years several researchers have examined potential trends in disaster loss data. They have documented a strong increase in disaster losses over the past several decades, ascribed largely to ime-variant socio-economic factors (Pielke et al. 2005). An adjustment procedure must be applied to detect any significant signal of change in disaster loss series. This implies an inflation correction as well as a normalization of disaster losses for changes in population and wealth. Indicators used for changes in wealth include Gross Domestic Product (GDP) per capita, property values and size of property market (Barredo 2010; Changnon 2011).

A recent assessment of disaster loss trend studies concluded, that although economic losses from weather-related disasters have increased worldwide over the past several decades, most studies have not found any trend in normalized losses that could be attributed to anthropogenic climate change (Bouwer 2011). Important uncertainties, howver, remain with respect to changes in exposure and vulnerability. Similarly, factors offsetting disaster losses, such as improved building codes, early warning systems, defense measures, disaster preparedness and response, and land-use planning, are still poorly quantified (Neumayer and Barthel 2011).

No systematic study on damage and loss exists for high-mountain slope failures, but both global and national event catalogues include some pertinent data. For instance, the Working Group on Glacier and Permafrost Hazards in Mountains (GAPHAZ) of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA) maintains a global catalogue of glacier hazards that includes, but is not limited to, high-mountain slope failures. The Swiss Permafrost Monitoring Network (PERMOS) has an inventory of rock slope failures in permafrost areas that includes damage information, although not systematically.

In conclusion, it is unlikely that any sound trend analysis can be performed with existing damage and loss data, largely due to the relatively rare occurrence of damaging high-mountain slope failures.

Case Studies

Although inventories and loss data may reveal changes in frequency or magnitude of events, they tell us nothing about the causes of the changes. Analysis of case studies, on the other hand, should provide insights into the driving processes at specific locations. Although there have been several media reports in recent years of mountaineers commenting on changes in rock fall activity along high-mountain climbing routes, little scientific evidence on such changes has yet been gathered.

In the Alps the record-breaking heat wave in the summer of 2003 coincided with strongly enhanced rock fall activity from permafrost areas, probably in relation with rapid thawing processes (Gruber et al. 2004). At Monte Rosa at the Swiss-Italian border, the frequency and magnitude of slope failures from bedrock and steep glaciers on the 2,500 m high east face significantly increased in the 1990s (Fischer et al. 2006). This change in mass movement activity was interpreted as a response to mass changes in relation with atmospheric warming in the 1980s and 1990s. Fischer et al. (2011) showed that the mass failures in rock and ice were coupled processes. Massive ice loss from steep glaciers mechanically and possibly thermally destabilized major rock slopes that had low rock strength or unstable geologic structures, and subsequently failed (Fischer et al. 2011).

Interesting evidence of a systematic change of rock slope failures from permafrost areas comes from the central Swiss Alps. Frequent rock falls started to occur in 2009 from the northeast face of Ritzlihorn (3,263 m asl) in the Grimsel area. Running water in bedrock couloirs together with numerous small-scale slope failures from the summit area during warm summer days (D. Tobler, personal communication, 2011) are likely evidence for the influence of thawing permafrost. Rock fall debris accumulates on less steep parts of the northeast face and on the apex of the large Holocene debris fan on which the community of Guttannen is located. At the time of the beginning of rock fall activity, repeated and large debris flows initiated at the fan apex. Antecedent soil saturation due to long-lasting snow is probably an important factor in triggering the debris flows. The largest debris flows, in July and August 2010, had volumes of ~100,000 m^3 and a peak discharge of ~500 m^3/s (Hählen 2010). A highway and a transnational gas pipeline were damaged by the debris flows and mitigation measures costing tens of millions Euros were initiated.

It is noteworthy that there were no historic damaging debris flows on the debris fan at Guttannen prior to 2009. This case study thus signals a dramatic change in a coupled high-mountain geomorphic system, with a possible attribution to impacts of climate change, although the attribution is difficult to quantify. Similarly, as at Monte Rosa, the

Table 1 Selected major rock slope failures and avalanches of the past two decades around the world. Events related to earthquakes are excluded. Existence of permafrost at the failure area is indicated, as well as occurrence of warm periods with temperatures close to or above freezing days and weeks before failure

Location	Date of occurrence	Approx. Volume (10^6 m^3)	Max. failure elevation (m asl)	Permafrost occurrence at failure	Warm period days-weeks before failure
Mt. Cook, New Zealand	14 Dec 1991	60	3,755	Yes	Yes
Brenva, Italy	18 Jan 1997	6.5	3,725	Yes	No
Kolka, Russia	22 Sept 2002	130	4,300	Yes	No data
Thurwieser, Italy	18 Sept 2004	2.5	3,570	Yes	No data
Mt. Steller, Alaska	14 Sept 2005	50	3,100	Yes	Yes
Tinguiririca	~Jan 2007	14	3,900	–	Yes
Mt. Rosa, Italy	21 April 2007	0.3	4,000	Yes	Yes
Mt. Steele, Canada	24 Jul 2007	27–80	4,640	Yes	Yes
Mt. Miller, Alaska	6 Aug 2008	22	2,200	Yes	Yes
Mt. Dampier, New Zealand	First week April 2010	0.5	3,400	Yes	Yes
Mt. Meager, Canada	6 Aug 2010	45	2,400	Likely	Yes

Ritzlihorn case study also indicates that an initial stimulus of climate change may be sufficient to alter a system in such a way that it can subsequently evolve independently of further climate impacts.

Causative and Trigger Factors

Another approach to detect changes in slope failures is to analyze potential changes in landslide predisposition and triggering factors and processes. For shallow landslides, intense and prolonged rainfall events with rapid infiltration into the soil, saturating it and generating high transient pore pressures are a main trigger (Iverson 2000). Important triggering parameters are total rainfall, rainfall intensity, rainfall duration, and antecedent rainfall (Wieczorek and Glade 2005; Sidle and Ochiai 2006). An important body of research exists on empirical rainfall landslide triggering (e.g. Guzzetti et al. 2007).

Rainfall is also recognized as a trigger of rock slope failures through mechanisms such as water infiltration and pressure variations in cleft systems (Wieczorek and Jäger 1996; Chau et al. 2003). Precipitation has been considered to be a likely trigger of high-mountain slope failures through water infiltration and possibly lock-off effects after refreezing (Fischer et al. 2010).

Temperature can have an important indirect effect on triggering or predisposing slopes to failure in high- mountain glacial and periglacial environments, where surface and subsurface ice is sensitive to short and longer term changes in temperature.

Related to longer term processes, inventory-based studies in the New Zealand and European Alps (Allen et al. 2011; Fischer et al. subm.,), have identified a prevalence of recent slope failure occuring from zones of warm, thawing permafrost (ca. >-1.5 °C) and/or from bedrock slopes influenced by recent glacial recession. Such studies have therefore provided an indirect, partly qualitative demonstration that predispositional processes related to climate warming have altered the distribution although not necessarily the frequency of recent high-mountain failures.

Concerning shorter time scales, recent studies of several large rock slope failures in Alaska, New Zealand and the Alps have shown that virtually all of the events were preceded by very warm temperatures, clearly above the freezing point, i.e. generating melt conditions (Huggel et al. 2010). Because these events are rare, it is difficult to detect a change in their frequency, and therefore attribute any direct influence of extreme temperature or precipitation as trigger mechanisms. However, very high temperatures, commonly expressed as the 90th or 95th percentile of the long-term record, have increased over the past 50–100 years over most land regions worldwide (Trenberth et al. 2007). In Europe, for instance, the frequency of hot days almost tripled between 1880 and 2005 (Della-Marta et al. 2007). Precipitation extremes have also increased in many parts of the world over the past several decades, but the changes vary more with season, and between regions (Trenberth et al. 2007). There is currently a lack of studies that specifically look at changes of extreme temperature and precipitation events in high mountain regions, partly due to limited long-term observation data (Table 1).

Climate Impact and Process Models

Detection and attribution of changes in landslides could, in principle, also be addressed through climate impact and process models along the lines of single-step or multiple-step attribution studies (IPCC 2010). For shallow landslides, where the link between slope failure and climate variable (rainfall intensity or duration) is reasonably clear, such an approach may be successful. In the case of past landslide events triggered by intense precipitation, one must demonstrate an attribution of high-intensity rainfall events to effects of anthropogenic greenhouse gas emissions, such as done by Zhang et al. (2007) for mean precipitation trends. The second step is to examine the attribution of landsliding to greenhouse-gas-induced heavy precipitation. This step would probably be done using multiple realizations, resulting in a probability-based assessment of attribution (Pall et al. 2011).

The attribution of high-mountain rock slope failures to anthropogenic warming is much more complicated and probably not feasible because the link between the climate variable (temperature or precipitation) and slope failure is not yet sufficiently understood or modeled. Models of permafrost distribution at the surface and depth have been used in combination with regional climate models, and past and future three-dimensional permafrost distribution could be modeled (Salzmann et al. 2007). Limited applications of mechanical slope stability models exist for rock slope failures in permafrost areas (Fischer et al. 2010), but explicit modeling of different effects of permafrost on rock slope stability has not yet been achieved. Thus, although the human influence on increasing temperatures is detectable in different regions around the world (Hegerl et al. 2007), any anthropogenic effect on high-mountain slope failures cannot yet been quantified.

Conclusions

The primary objective of this paper was to outline a number of approaches that potentially can be used to detect a change in landslide activity, more specifically, landslide activity in high mountains. Although recent studies have found changes in the occurrence of alpine rock slope failures over the past several decades, the research is in its infancy. A limited number of studies, have examined possible changes in frequency or magnitude of shallow landslides or debris flows. The methodological approaches described here have not been rigorously tested in high-mountain environments. However, several of the presented approaches, including the analysis of slope failure inventories, case histories and trigger factors, are promising avenues for detection studies. The last methods presented here, which refer to attribution of observed changes to anthropogenic climate change, might currently hardly be applicable for complex high mountain slope stability problems. They could be used, however, if our under standing of processes improves.

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