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# Climate change impacts on mass movements — Case studies from the European Alps

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## HIGHLIGHTS

- Thawing permafrost negatively affects periglacial debris flows and rock failures.
- Events without historical precedents can occur from unstable permafrost environments.
- Debris flows are likely to occur more often in spring and fall, but less in summer.
- Shallow landslides will occur more often in early spring, but in smaller overall numbers.
- Fall landslides with large spatial densities of occurrences are likely to become scarcer.

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## ABSTRACT

This paper addresses the current knowledge on climate change impacts on mass movement activity in mountain environments by illustrating characteristic cases of debris flows, rock slope failures and landslides from the French, Italian, and Swiss Alps. It is expected that events are likely to occur less frequently during summer, whereas the anticipated increase of rainfall in spring and fall could likely alter debris-flow activity during the shoulder seasons (March, April, November, and December). The magnitude of debris flows could become larger due to larger amounts of sediment delivered to the channels and as a result of the predicted increase in heavy precipitation events. At the same time, however, debris-flow volumes in high-mountain areas will depend chiefly on the stability and/or movement rates of permafrost bodies, and destabilized rock glaciers could lead to debris flows without historic precedents in the future. The frequency of rock slope failures is likely to increase, as excessively warm air temperatures, glacier shrinkage, as well as permafrost warming and thawing will affect and reduce rock slope stability in the direction that adversely affects rock slope stability. Changes in landslide activity in the French and Western Italian Alps will likely depend on differences in elevation. Above 1500 m asl, the projected decrease in snow season duration in future winters and springs will likely affect the frequency, number and seasonality of landslide reactivations. In Piemonte, for instance, 21st century landslides have been demonstrated to occur more frequently in early spring and to be triggered by moderate rainfalls, but also to occur in smaller numbers. On the contrary, and in line with recent observations, events in autumn, characterized by a large spatial density of landslide occurrences might become more scarce in the Piemonte region.


## 1. Introduction

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) states that the number of warm days has likely increased at the global level and that heat waves and heavy precipitation events have increased in Europe since 1950 (IPCC, 2013). Hot temperatures are thereby usually expressed as the 90th or 95th percentile of the long-term record (Trenberth et al., 2007). In high-mountain regions, the evolution of mean and extreme temperatures will likely be comparable or even larger than the global mean. Allen and Huggel (2013) have recently shown a strong increase of extremely warm temperatures at some high elevation sites in Switzerland over the past decades, but also pointed to the general lack of studies specifically focusing on trends at higher elevations.

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Significant changes may also be expected in precipitation, as the capacity of air to hold moisture is a function of temperature. In general terms global warming is therefore likely to lead to an overall greater frequency and magnitude of heavy precipitation events (e.g., Fowler and Hennessy, 1995; O'Gorman and Schneider, 2009; Schneider et al., 2010), although locally substantial uncertainties will remain regarding rainfall frequency and magnitude (Fischer et al., 2013). Available observations indicate an increase in the frequency and intensity of extreme precipitation events in different sets of observational data from several regions of the world (IPCC, 2012). For the future, projections suggest decreasing return periods of extreme rainfall events but with the remaining, aforementioned uncertainties on a local level (Christensen and Christensen, 2003; Kharin et al., 2007; Kyselỳ and Beranovà, 2009; Orlowsky and Seneviratne, 2012; Fischer et al., 2013). In the case of the European Alps, complex topography poses considerable challenges to climate models, which typically translate to uncertainties in climate projections of future temperatures, and even more so for changes in precipitation.

Mean and maximum air temperatures have increased considerably in the past few decades and related average temperatures in Europe have been warmer than in any comparable period during – at least – the last 2000 years (PAGES 2k consortium, 2013). With ongoing climate change, mean and extreme temperatures are expected to continue to rise considerably over the next decades (IPCC, 2012). Under the A1B emission scenario, Gobiet et al. (in press) project a decadal warming of 0.25 °C until the mid-21st century. The warming trend is expected to accelerate during the latter half of the century for which they assessed an average temperature increase of 0.36 °C per decade. Changes in the seasonality of precipitation are likely to be associated with the projected warming, as will global radiation, and relative humidity. Gobiet et al. (in press) also state that the conditions of currently record breaking warm winter and/or hot summer seasons may become normal at the end of the 21st century. As a direct consequence of further warming, snow cover duration will likely decrease drastically below 1500–2000 m.

Changes in air temperature and precipitation are considered likely to have a range of secondary effects, including on the subsurface temperature and three-dimensional distribution of permafrost as well as on the stability of slopes (Stoffel et al., 2005a; Stoffel and Huggel, 2012). However, while there is theoretical understanding for increased mass-movement activity as a result of predicted climate change in mountain environments, changes in activity are difficult to detect in observational records. In addition, uncertainty remains considerable as a result of error margins inherent to scenario-driven global projections, and due to the coarse spatial resolution of available downscaled model data (Crozier, 2010). Warmer air temperatures are also likely to promote the downwasting of permafrost bodies in the mean to long term (Salzmann et al., 2007), which in turn may liberate additional sources of unconsolidated material and/or favor the occurrence of rockfalls (Harris et al., 2009), as evidenced by the release of a number of recent, large-magnitude debris flows in the Alps beyond historical experience (Stoffel and Huggel, 2012).

At lower elevations, the frequency and magnitude of landslides have been reported to decrease as a result of climate change (Collison et al., 2000; Dehn et al., 2000). For a site in the French Alps, Malet et al. (2007) found that the effects of future climate change on slope stability strongly vary with local conditions. In general, however, such information remains scarce for higher-elevation sites of the European Alps.

In the framework of the EU-FP7 ACQWA project (www.acqwa.ch), several research teams have addressed the impacts of changing climatic conditions on the headwater catchments of the Rhone and Po basins in general (Beniston et al., 2011; Beniston and Stoffel, in press; Fatichi et al., in press; Pellicciotti et al., in press), but also in terms of temporal frequency and ensuing magnitude of mass movements. This contribution aims at reviewing and illustrating possible changes in the occurrence of debris flows, landslides and rockfalls for selected regions of the Swiss, Italian, and French Alps, based on large sets of observational records and/or statistically downscaled climate data (Gobiet et al., in press).

## 2. Periglacial debris flows in the Swiss Alps

Projected changes in mean and extreme temperatures and precipitations are likely to influence the temporal frequency and magnitude of mass wasting processes in mountain environments (IPCC, 2012; Gobiet et al., in press). This is especially true for processes driven by water, such as debris flows, where changes in rainfall intensity and duration, in combination with higher temperatures, are thought to lead to enhanced process activity, provided that sediment is not limited and that the occurrence of events is driven primarily by water input above a certain threshold (Stoffel and Huggel, 2012; Borga et al., in press). A warmer climate also results in higher 0 °C isotherms, thus allowing for more precipitation to fall in liquid form even in the uppermost portions of mountain catchments, thereby increasing the area contributing effectively to runoff (Beniston, 2005; Stoffel and Beniston, 2006). At the same time, however, increasing air temperatures might allow vegetation to grow at higher altitudes and to stabilize loose material (Baroni et al., 2007), provided that ground conditions are more or less stable and that slope gradients are not too steep.

Debris flows in high mountain areas are commonly initiated by the mobilization of sediment stored in channels or by shallow landslides through the sudden input of large amounts of water, such as rainstorms, rapid snow melt, rain-on-snow events, or the sudden release of water from glaciers or (landslide) dammed lakes (e.g., Sassa, 1984; Iverson et al., 1997; Wieczorek and Glade, 2005; Worni et al., 2013). Most commonly, however, debris flows in the Alps have been triggered by high-intensity, short-duration rainstorms or low-intensity, long-duration precipitation events in the past (Stoffel et al., 2011; Schneuwly-Bollschweiler and Stoffel, 2012; Toreti et al., 2013).

The focus of this study is on past and possible future debris flows in the Zermatt valley, a dry inner-alpine valley of the Valais Alps (Switzerland, 46°10′N., 47°7′E.; Fig. 1), where the temporal frequency and triggers of debris flows have been studied in detail for eight high-elevation, small torrential catchments. The Zermatt valley has a north–south orientation and is bordered to the south by high mountains reaching up to 4634 m asl. The regional climate is typically dry and cool with average annual precipitation of 533 mm in Ackersand (1961–2008; 700 m asl), 570 mm in Grächen (1864–2008; 1605 m asl) and 690 mm in Zermatt (1900–2008; 1638 m asl). Mean annual temperature is 6.0 °C in Grächen and 4.2 °C in Zermatt (mean for the last climate normal 1981–2010). January through April are generally the driest months with 30–40 mm each on average, whereas October is commonly the wettest month with 63 ± 52 mm of precipitation (MeteoSwiss, 2013).

All catchments face west and have a very similar geomorphic setting (for details see Schneuwly-Bollschweiler and Stoffel, 2012). Permafrost is present in the source areas of all catchments, and the uppermost reaches of three torrents (Wildibach, Dorfbach, Birchbach) are glaciated. The catchments reach elevations of up to 4545 m asl, and the initiation zones of debris flows are located between 2000 and 3000 m asl. The principal sediment sources for periglacial debris flows are extensive moraine deposits, scree slopes and rock glaciers within permafrost environments.

Debris-flow occurrence in the area is typically restricted to late spring, summer, and early fall. High annual and daily thermal ranges favor weathering related to cycles of freezing and thawing as well as regolith production delivered to scree slopes (Hall et al., 2002; Hall and Thorn, 2011). Slope angles in the initiation zones reach 27–41° (mean 32.6°). Permafrost in the loose sediment of the source areas of debris flows forms impermeable layers which promote drainage along preferential paths (Krainer and Mostler, 2002). During rainstorms, water (and ice melt) is released to the torrent along the contact with the permafrost body. Rainstorms can trigger debris flows either through

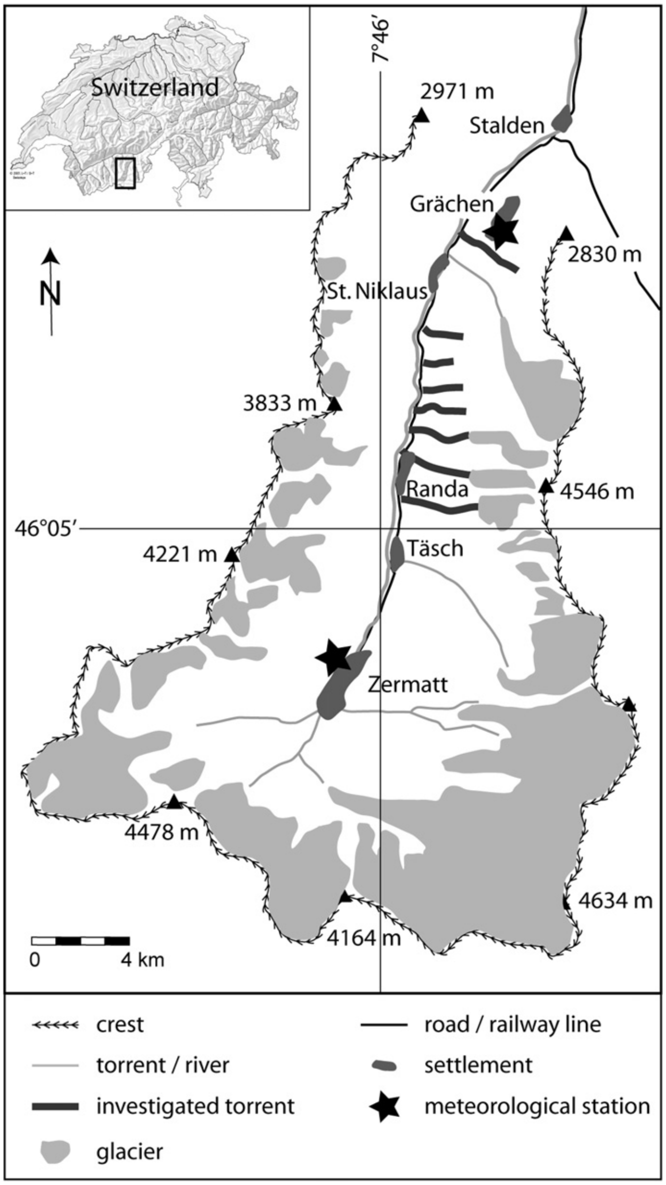


**Fig. 1.** Debris flow sites in the Zermatt valley with meteorological stations (Grächen, Zermatt) used for the analysis of triggering conditions. The eight torrents analyzed are highlighted with thick gray lines and are (from North to South): Ritigraben, Grosse Grabe, Bielzug, Fallzug, Geisstriftbach, Birchbach, Dorfbach, and Wildibach (modified from Stoffel et al., 2014).

the wetting of material (Griffiths et al., 1997) continuously delivered by permafrost to a channel or by promoting failure of rock glacier (snouts) along an impermeable ice layer (i.e. active layer) during exceptional water input (Larsson, 1982; Sattler et al., 2011). In both cases, debris flows are thought to occur through a liquefaction mechanism similar to that described for shallow landslides (Sassa, 1984; Fleming et al., 1989; Iverson et al., 1997). In addition to being triggered by rainfall, debris flows at high-elevation sites also occur when sediment shear resistance is reduced by the melting of ice particles (Arenson and Springman, 2005) and by the delivery of fine-grained sediment formerly frozen in the ice matrix (Rist, 2001).

Following initiation, debris flows in the Zermatt valley normally pass through steep channels with slope angles of 22–33° (mean 27.6°); they are either deposited on debris-flow cones located on the valley floor (1200–1400 m asl) or directly transported to the Vispa river. A slightly different setting exists for Ritigraben (Fig. 1) because its cone is situated on a structural terrace located above the valley floor at 1460–1800 m asl (Stoffel et al., 2008). The proportion of debris-flow sediment originating from the initiation zones commonly has been reported to be one order of magnitude smaller than the total debris-flow volume deposited on the cone (Stoffel, 2010). However, where active-layer failures are the cause, up to one-third of the total debris-flow material is released from the rock glacier front (Fig. 2; Lugon and Stoffel, 2010). Channel erosion thus adds considerable amounts of material to debris-flow volumes (Stoffel, 2010).

Frequency data on past debris flows were gathered from archives, or reconstructed from tree-ring records of damaged conifers (e.g., Stoffel and Bollschweiler, 2008; Bollschweiler and Stoffel, 2010a; Stoffel et al., 2013; Stoffel and Corona, 2014). The database was built with tree-ring records from 2467 conifers (mainly *Larix decidua* and *Picea abies*; Stoffel et al., 2005c, 2008, 2010; Bollschweiler et al., 2008a; Bollschweiler and Stoffel, 2010b; Sorg et al., 2010; Schneuwly-Bollschweiler et al., 2013) covering the period AD 1600–2009. The database, presented in Fig. 3, contains a total of 417 events in 226 different years. A total of 296 debris flows has been recorded after 1850 when activity could be observed in at least one of the torrents in the valley in 84% of the years (i.e. 134 out of 160 years showed activity). Decadal frequencies show a mean of 18.6 events and suggest peaks in debris-flow activity after the end of the Little Ice Age (ca. 1855–1860 in the wider study region; Holzhauser, 2008) and for the period 1920–1929 (27 events). By contrast, activity was rather low during the most recent part of the record (2000–2009) when only 13 events have been recorded in the valley (Stoffel and Beniston, 2006; Bollschweiler and Stoffel, 2010c; Stoffel et al., 2011).

At the meteorological station of Grächen, where daily precipitation measurements extend back to 1864, heavy precipitation events (exceeding 50 mm day$^{-1}$) occur roughly one year in four, and this trend has not changed in the recent part of the record (Beniston, 2006). While there are no trends visible in the frequency of heavy rainfall events, we observe a cluster of advective storms in late summer and early fall since the late 1980s which would have resulted in the triggering of debris flows mostly by advective rains and less frequently during thunderstorms over the past 25 yr. This observation is in strong contrast to the 1950s, 1960s and 1970s, when debris flows were released by convective storms (Stoffel et al., 2011) and also in contradiction with recent work by Berg et al. (2013). These changes in triggering meteorological conditions, presented in Fig. 4, likely reflect the observed changes in extreme pressure systems and their persistence over the Alps, with significant associated temperature and precipitation anomalies during the positive phase of the NAO and related changes in the circulation patterns that affect the Alps (Beniston and Jungo, 2002).

Years with activity in all eight torrents could not be identified, but six out of eight torrents have released debris flows simultaneously in 1993, 1970, 1945, and 1920. Conditional probabilities indicate that the occurrence of debris flows at Ritigraben is one in two ($p = 0.51$) on average if an event occurred in any other torrent in the valley (Stoffel et al., 2005c; Bollschweiler and Stoffel, 2010c). In a similar way, probabilities are increased to identify a reconstructed debris-flow occurrence in the Geisstriftbach and Wildibach if there was an events in any of the other torrents ($p = 0.45$). Recurrence intervals vary considerably between the torrents, with the Ritigraben exhibiting the largest activity with a mean recurrence interval of 3.24 years over the period 1600–2009. For the Bielzug and Fallzug and based on the tree-ring reconstructions, 7.21 (1840–2009) and 9 years (1890–2009), respectively, pass on average between two events (Bollschweiler and Stoffel, 2010c).

For a total of 116 debris flows occurred between 1864 and 2008 – data were gathered from archival records and tree-ring analysis – we analyzed meteorological conditions leading to the events. Archival records indicating the day of the event were available for 22 (19%) debris flows. For the 94 (71%) other events, the possible time window of events was assessed via the intra-annual position of debris-flow injuries or the occurrence of tangential rows of traumatic resin ducts (TRD;

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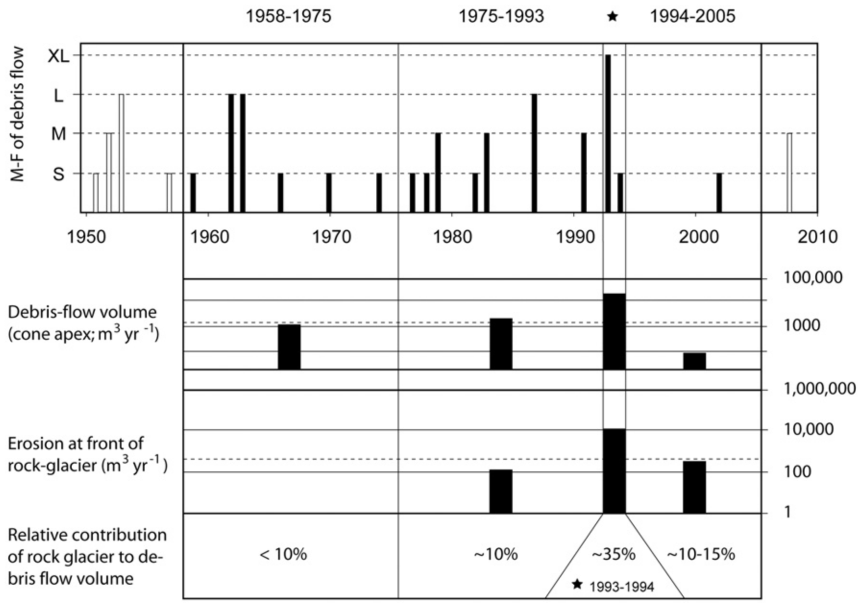


**Fig. 2.** Sediment delivery of the rock glacier in the source area of debris flows at Ritigraben (for details see map in Fig. 1) and M–F relationships of debris flows on the depositional cone. Not more than 10% of the total volume of debris flows is usually released from the source area, unless an active failure of the rock glacier front occurs, thereby contributing substantial amounts of sediment and water into the debris-flow system. Such an active layer failure has been observed in 1993 and resulted in a series of huge debris flows in 1993 (modified from Lugon and Stoffel, 2010).

Bollschweiler et al., 2008b; Schneuwly et al., 2009a, 2009b) in the growth series of trees growing on the debris-flow cones. The intra-annual position of injuries and TRD therefore allows event dating with up to monthly precision (Stoffel et al., 2005b; Stoffel, 2008; Stoffel and Hitz, 2008). Rainfall data from the Grächen and Zermatt meteorological stations (see Fig. 1 for details) and runoff data from stream gauges were then examined within the temporal range suggested by the tree-ring records to identify the rainfall events which would have triggered debris flows. We excluded rainy days with maximum temperatures <5 °C as precipitation was likely in the form of snow in these cases in the source area of debris flows. As the study region is located in a dry environment with only 7.7 days with P > 10 mm and T ≥ 5 °C between May and October at Grächen (9 and 6 days for Zermatt and Ackersand, respectively), identification of triggering rainfalls within the period suggested by injuries and TRD was usually straightforward. River runoff data was used to cross-check the definition of triggering rainfalls. Based on the analysis of debris flows dated to the day, it was possible to demonstrate that the debris-flow season at these high-altitude sites now is much longer (May to October) than it used to be in the late nineteenth century when activity was limited to June–September. The earliest event on record occurred on 18 May 1960 (Julian day 139), the latest event on 29 October 1913 (Julian day 302), with a mean on Julian day 215 (August 3). Over the past ~150 yr, most debris flows were released in July and August (60.2% of all events), but were also common in June and September (18% and 12%, respectively). Events were, by contrast, rather scarce very early and late in the debris-flow season with 3% and 7% in May and October, respectively (Fig. 5; Schneuwly-Bollschweiler and Stoffel, 2012). Between 1864 and 1899, a vast majority of debris flows was triggered in July and August (or JA; 76% in total) and no debris flows occurred in May and October. The first debris flow in May is recorded for 1923 and the first in October for 1911. During the most recent time interval (1972–2008), debris flows become more frequent early (May) and late (October) in the season with 17% of all events, whereas debris flows have become less abundant in JA (51%). In the case of the Ritigraben, the occurrence dates of events have shifted by almost four weeks since the late nineteenth century (i.e., from Julian day 207 to 234; mean: 223, max: 275, min: 151, SD: 29.8 days). This offset of activity from summer to late summer and early fall is also obvious when the incidence of debris flows is analyzed on a monthly scale for which we observe a significant shift of events away from early June and July to August and September. This temporal shift in debris-flow occurrences becomes already obvious at the beginning of the last century, when warm-wet summers between 1916 and 1935 favored the release of debris flows later in the season and prevented early-season flows in

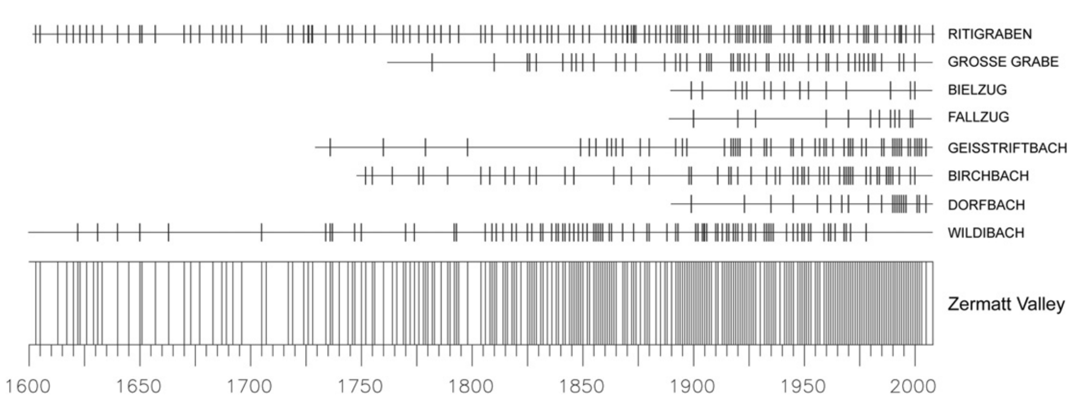


**Fig. 3.** Debris-flow frequencies for the eight torrents of the west-exposed slopes of the Zermatt valley (top) and the composite for the valley-wide reconstruction (bottom). Data is from tree-ring reconstructions and each bar represents an event in one torrent (modified from Bollschweiler and Stoffel, 2010c).

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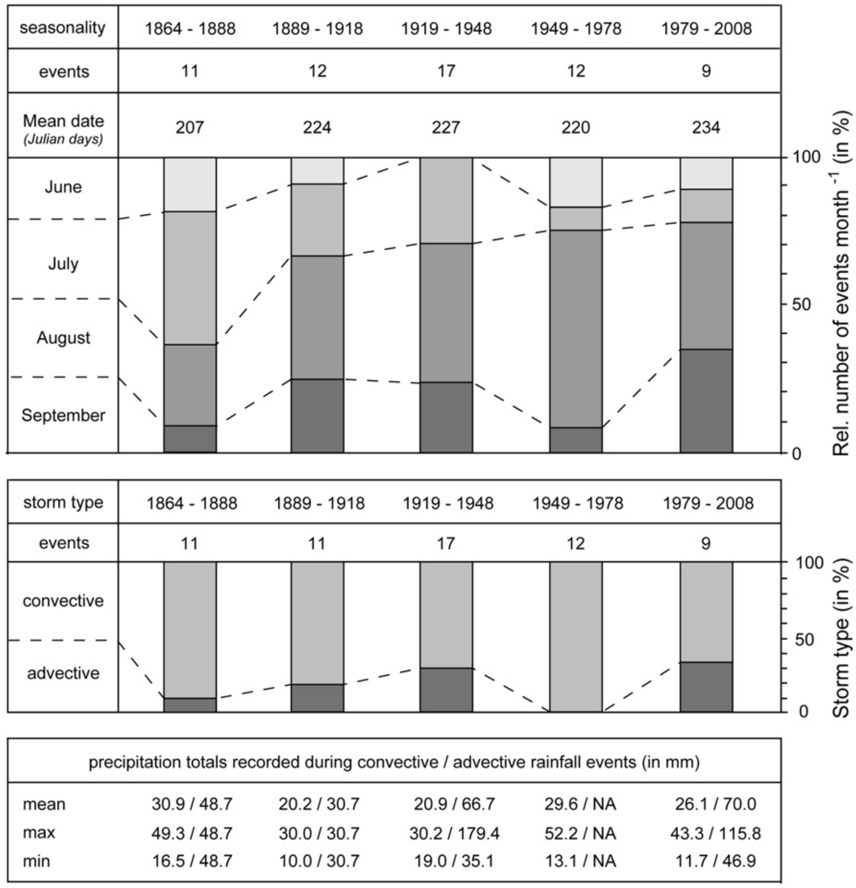


**Fig. 4.** Changes in seasonality of debris-flow events (top) in the Ritigraben torrent (for details see Fig. 1 and text), storm types triggering debris flows (center) and rainfall totals recorded during convective and advective storms with subsequent debris-flow releases (bottom) (modified from Stoffel et al., 2011).

June. As a result of a temporal cooling tendency in the 1960s, occurrence dates dropped again to below-average values (AD 1949–1978). For the most recent past, data again indicate a very pronounced offset of occurrence dates with a mean value of 234 Julian days and a predominance of August and September debris flows (Stoffel et al., 2005c, 2011).

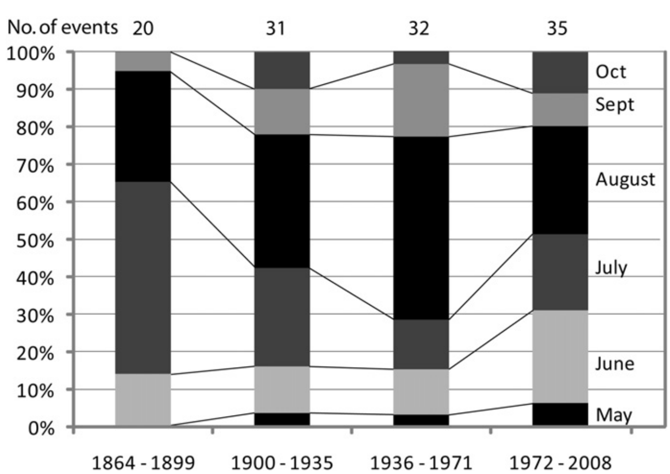


**Fig. 5.** Evolution of the temporal occurrence of debris flows between 1864 and 2008 in the Zermatt valley. Each bar represents an equally long time interval (35 years; 36 for 1972–2008) and the percentage of debris flows occurring per month (May–October). Total number of debris flows per period is given on top of the bars. Whereas no debris flows occurred in May and October between 1864 and the end of the 19th century, 18% of all debris flows now occur very early (May) or very late (October) in the debris-flow season (modified from Schneuwly-Bollschweiler and Stoffel, 2012).

Analyses also showed that debris flows early in the season are generally triggered with lower rainfall totals (<20 mm in 1 day) than those occurring late as snow melt adds considerable amounts of water to the system and therefore facilitates debris-flow release (Stoffel, 2010; Stoffel et al., 2011). A majority of debris flows was released by short-lived rainfalls (≤1 day; mostly local thunderstorms). This is particularly true for May, June, July and August when 50–60% of all events fall into this category, whereas the occurrence of debris flows late in the season (September and October) is more often related to longer-lasting advective rainfalls. Longer-lasting precipitation events (3-day events) were rather scarce in general and especially during the initial months of the debris-flow season and in summer (May through August). In JA, less than 10% of all events were triggered by 3-day rainfalls, but these events become more crucial in SO when they are responsible for the release of one-third of the debris flows (Schneuwly-Bollschweiler and Stoffel, 2012).

As the torrents under investigation have (almost) unlimited sediment supply, the triggering of debris flows is mainly controlled by climatic factors. Based on point-based downscaled climate scenarios for the meteorological stations of Grächen and Zermatt and for the periods 2001–2050 and 2051–2100, the evolution of temperature and rainfalls above specific thresholds (10, 20, 30, 40, and 50 mm) as well as the duration of precipitation events (1, 2, or 3 days) have been studied. The analysis of temperature and precipitation changes reveals a drying tendency for future summers and more precipitation events during the shoulder seasons (Stoffel et al., 2014). Projections are in concert with the observations of Schmidli and Frei (2005) who reported a shift in precipitation seasonality in the observational records. At the same time, despite the general decrease in precipitation sums in summer, we observe an increase in the occurrence of heavy (>40 mm) 1-day

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precipitation events in the region, which is in line with results of the RCM-based study on extreme precipitation events in Europe by Christensen and Christensen (2003). In conclusion, the drier conditions in future summers and the wetting of springs, falls and early winters are likely to have significant impacts on the behavior of debris flows.

Based on the current understanding of the debris-flow systems and their reaction to rainfall inputs, one might expect only slight changes in the overall frequency of events by the mid-21st century, but possibly an increase in the overall magnitude of debris flows due to larger amounts of sediment delivered to the channels and an increase in extreme precipitation events. In the second half of the 21st century, the overall absolute number of days with conditions favorable for the release of debris flows will likely decrease, especially in summer. The anticipated increase of liquid rainfalls during the shoulder seasons (March, April, November, December) is not expected to compensate for the decrease in future heavy summer rainfalls over 2 or 3 days in absolute terms, but magnitudes, in contrast, can be expected to increase in the study area. The volume of entrained debris from the source areas tends to be larger in summer and fall when the active layer of the permafrost bodies is largest and allows for larger volumes of sediment to be mobilized (Lugon and Stoffel, 2010), but the situation has been shown to depend also on the stability and climate change-related accelerations of rock-glacier bodies (Stoffel and Huggel, 2012). Along with the occurrence of more extreme precipitation events, these rock-glacier instabilities could lead to debris flows without historic precedents in the future (Fig. 6).

## 3. Large, high-elevation rockfalls in the Swiss and French Alps

Research on high-mountain rock slope failures has gained increasing momentum over the past several years. The European Alps are one of the research hotspots because of the long-standing tradition in mountain permafrost studies (Gruber and Haeberli, 2008), and because of the relatively high exposure of people and infrastructure to mass movement hazards in the Alps (Haeberli, in press). Several studies have documented recent events of rock slope failures in the Alps (Allen and Huggel, 2013; Huggel et al., 2012; Ravanel and Deline, 2011; Ravanel et al., 2010) and in other high-mountain regions of the world (Arsenault and Meigs, 2005; Geertsema et al., 2006; Huggel et al., 2010; Allen and Huggel, 2013; Uhlmann et al., 2013).

Generally speaking, rock failure occurs when shear stresses overcome shear strength of a rock mass. Failure typically evolves along pre-existing rock cleft and discontinuity systems, and geology is therefore one of the important basic factors that conditions rock mass stability. Topography, geomechanics, hydrology and weather conditions are further influencing factors, and in high-mountain regions, there are additional factors related to permafrost and glaciers (Fischer and Huggel, 2008). While geology is relatively stable over larger time periods, glaciers and permafrost change much faster, as observed under current conditions of climate change. Considering different time scales is particularly important when assessing slope stability in high mountains. Some contemporary rock slope failures were a response to deglaciation processes at the end of the last Ice Age in the form of unloading effects (Ballantyne, 2002; Fischer et al., 2010; Korup et al., 2012; Willenberg et al., 2008). Effects of deglaciation since the Little Ice Age (i.e. approximately two orders of magnitude shorter time scales) can be seen at some recent slope instabilities in the Alps, such as at Lower Grindelwald or Great Aletsch glacier (Oppikofer et al., 2008; Strozzi et al., 2010). Recent research has also focused on the potential effects of extremely warm temperatures on observed rock slope failures and found that many events in the Alps, Alaska and New Zealand were preceded by several days of unusually warm conditions (e.g. 90th or 95th percentile of the longer term record; Huggel et al., 2010; Allen and Huggel, 2013). This relation seems to be stronger for rock slope failures with volumes of $10^3$ to $10^5$ $m^3$ than for large ones (>$10^6$ $m^3$), but the statistical basis is still too weak to derive more definite conclusions in this respect (Allen and Huggel, 2013). The physical processes involved are thought to be related to melting of snow and ice, penetration of melt water into cleft systems resulting in a reduction of shear strength and enhanced slope deformation, which could recently be confirmed by multiple-sensor measurements at a local site at Matterhorn (Hasler et al., 2012). Nevertheless, in consideration of the multiple factors that affect rock slope stability it is generally difficult to attribute a particular event to one factor (Huggel et al., 2013).

Further evidence of climate change impacts on high-mountain rock slope stability comes from the analysis of documented slope failure events in the Alps since 1900 (Huggel et al., 2012). An inventory of >50 events with specified failure volumes has been compiled based on scientific publications, media reports, and diverse field observations. A related database with more than 150 events is currently maintained and further extended by the Swiss Permafrost Monitoring Network (PERMOS). The record of rock slope failures spanning a period since the beginning of the 20th century primarily indicates a sharp increase of the number of events since 1990 (Fig. 7). Monitoring and documentation efforts for rock slope failures have been intensified during the past ~20 years which induces a certain bias in the documentation as compared to time periods earlier in the 20th century. This is especially true for small rockfall events. However, it is likely that the documentation for large slope failures (>100,000 $m^3$) is reasonably complete over the 20th century, and the observed trends also hold true for the category

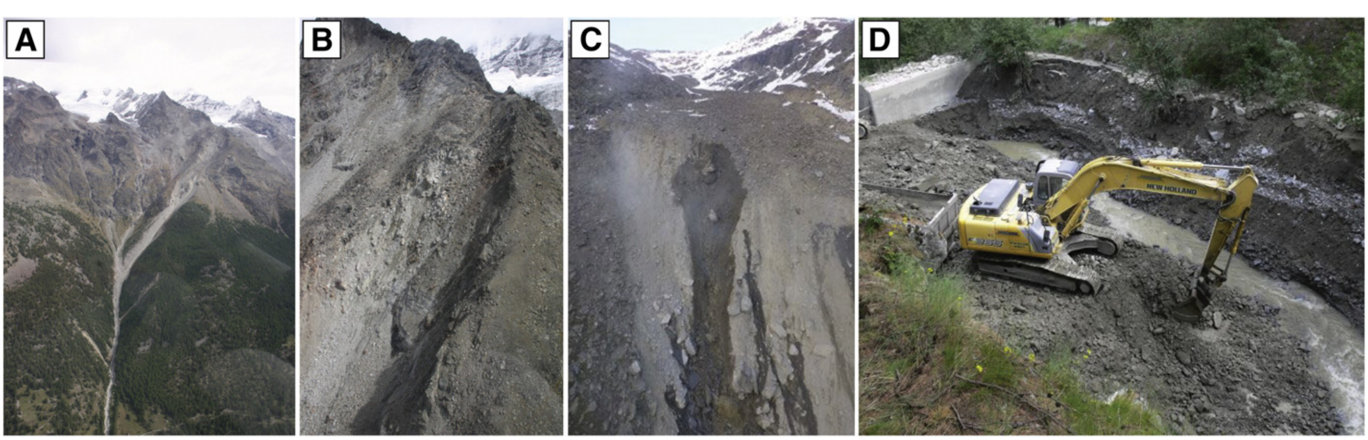


**Fig. 6.** Rock glacier instabilities in the Zermatt valley have had a severe impact on debris-flow frequency and magnitude in several torrents of the Zermatt valley: (A) Destabilization of a rock glacier front in the Dorfbach (Randa) has resulted in increased sediment availability in the torrent with subsequent increase in debris-flow activity. (B) Detailed view of the rock glacier front in the Dorfbach. (C) Increased melting of the permafrost in spring 2013 has led to accelerated rock glacier movements and wetting of the sediments in the rock glacier of the Bielzug (Herbriggen) with (D) subsequent and increased debris-flow activity in the channel.

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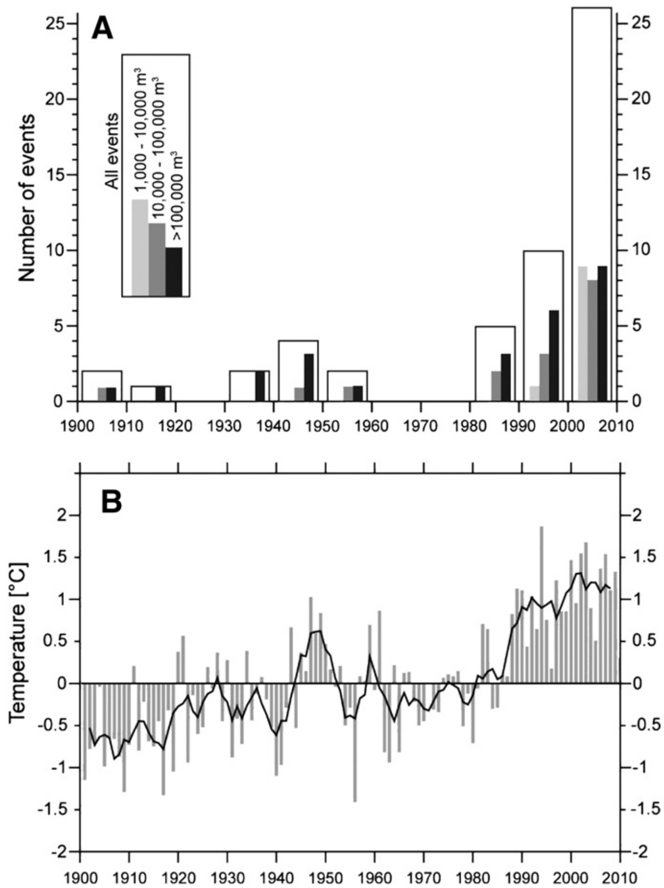


**Fig. 7.** (A) Record of number of rock slope failures between 1900 and 2010 in the central Alps. Three different volume classes are indicated. (B) A temperature record for a compiled dataset that averages conditions in Switzerland (departure of mean annual temperature from the 1960–1990) (modified from Huggel et al., 2012).

of large volumes (for an example of a recent large rock slope failure refer to Fig. 8). The frequency pattern across a regional inventory of the central Alps is also corroborated by detailed local studies in the Mont Blanc area (Huggel et al., 2012; Ravanel and Deline, 2011). Furthermore, it is interesting to note that the distribution of rock slope failures resembles the trends of mean annual temperature across Switzerland (Fig. 7). Although a statistical correlation is not suitable, this may be a further indication of temperature sensitivity of rock slope stability in high mountains that should be further investigated.

The suite of evidence coming from the aforementioned observation and modeling studies strengthens the physical understanding of high-mountain rock slope failures, and corroborates the sensitivity of rock slope failures to climate variability and change, and impacts of climate change on the cryosphere, namely glaciers and permafrost. Specifically, they indicate that (i) extremely warm temperatures, (ii) glacier shrinkage and downwasting, and (iii) permafrost warming and thawing affect and reduce rock slope stability. If we juxtapose these findings with the most recent assessment undertaken by the IPCC in the frame of AR5, we realize that in the course of the next decades (i)–(iii) will change even further with probability ranges of 90–100% (IPCC, 2013) in the direction that adversely affects rock slope stability.

## 4. Landslides in the French Alps and Piemonte (Italy)

Slope stability, and hence landslide activity, is primarily controlled by groundwater and fluctuations in pore-water pressure (Dehn et al., 2000). An increase in rainfall may thus affect hillslope stability through dynamic loads during high-intensity rainstorms, slope undercutting, or the redistribution of topography-induced stresses in rock slopes (Ballantyne, 2002). As a consequence, landslides are a process with causal links to climate change, primarily through precipitation, but in some cases also through temperature-induced changes of snowfall (Huggel et al., 2012).

Nevertheless, research into the detection of changes in landslide activity over the past several decades of observed atmospheric warming as well as the identification of factors controlling climate-driven changes in landslide magnitude and frequency remain rather scarce (Huggel et al., 2012). For the Central Swiss Alps, for instance, Meusburger and Alewell (2009) reported an increase of landslide events due to an increase of intense torrential rainfalls since the 1960s. At the same time, however, Hilker et al. (2009) reported no significant change of process activity for all of Switzerland. For the Italian Alps, archival records show an increase of landslide activity since the mid-19th century, but this change might be related to both a greater availability of historical data and changing vulnerability in increasingly urbanized areas (Tropeano and Turconi, 2004).

Based on a unique set of tree-ring data from 3036 increment cores, Lopez Saez et al. (2013a) observed a significant and unprecedented increase in the number of landslide reactivations in the Ubaye valley (French Alps) since the early 1990s (Lopez Saez et al., 2012a, 2012b, 2013b). Analysis of meteorological records extending back 120 yr indicate that the probability of landslide occurrence would have been strongly related with December and/or winter precipitation totals in the past, but that no significant correlation would exist with maximum daily and 3-day precipitation totals. Spring temperature seems to play a crucial role as well with high frequencies of landslide reactivations being observed in springs with positive temperature anomalies. Lopez Saez et al. (2013a) thus hypothesize that the combined effect of abundant winter precipitation and increased snowmelt represented the

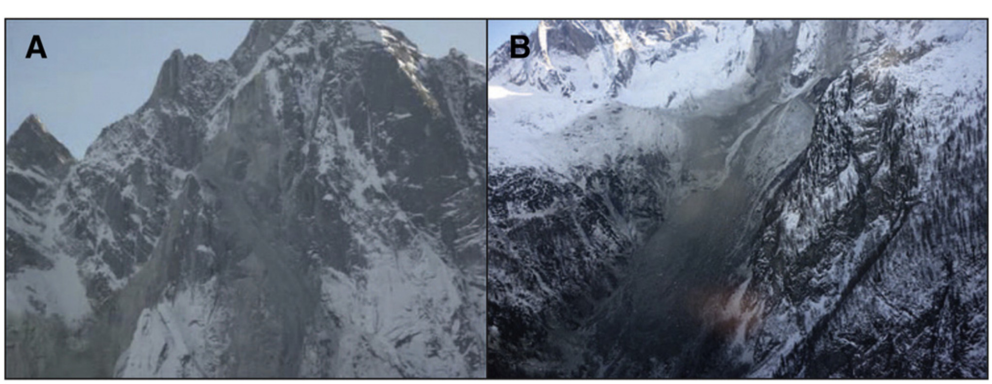


**Fig. 8.** A major rock slope failure occurred on 27 December 2011 from Pizzo Cengalo (3369 m asl) in the Val Bregaglia region, southeastern Alps. (A) The rock slope failure zone is located in permafrost areas. (B) The ~1.5 million m$^3$ of rock debris deposited along the Val Bondasca which were later repeatedly mobilized during heavy rainfall events and implied a dramatic change in debris-flow frequency and magnitude with serious effects down to the residential areas of Val Bregaglia (photos: Amt für Naturgefahren Graubünden, Heli Bernina).

main triggers of landslides in the Ubaye region in the past. The sharp increase in landslide activity after 1990, by contrast, is no longer apparently driven by winter precipitation totals or snow-cover duration (Durand et al., 2009), but clearly reflective of the unprecedented and sustained increase (~1 °C) of spring temperatures since the late 1980s. Lopez Saez et al. (2013a) thus conclude that the largely positive anomalies of recent spring temperatures would have altered the snow-to-rain ratio which would in turn have affected the timing of the critical snowmelt period, thereby leading to more frequent reactivations of shallow spring landslides in the study region. Based on data of IPCC emission scenarios B1, A1B, and A2, spring temperatures are expected to increase by ca. 1.4–1.7 °C and 2.3–4.3 °C for the periods 2021–2050 and 2071–2100, respectively, in the Ubaye Valley (Rousselot et al., 2012), which in turn will reduce snow water equivalents quite drastically. In the case of scenario B1, Lopez Saez et al. (2013a) expect the moderate diminution of the snow cover to result in more frequent landslide reactivations by 2050. According to the authors, however, climate change might ultimately cause a diminution if not complete disappearance of a permanent snow cover at 1800 m asl (predicted in all SRES scenarios) by the end of the century.

Analysis of landslides from Piemonte (northwestern Italy) adds further evidence to the observed changes in triggering climatic conditions and their impact on landslide frequency. Here, landscapes are dominated (73%) by mountain and hillslope environments, mostly located in three concentric arcs open towards the east: the Western Alps, the head of the Po valley as well as the heights of the Torino Hill, Langhe and Monferrato. The complex orographic setting defines and regulates the climate of Piemonte and causes a great variability of precipitation (Biancotti and Bovo, 1998). Historical data extending back to AD 1700 demonstrate that the region has always been affected by extreme rainfall events and related shallow landslides. Despite their comparably small size (commonly <1000 $m^3$) and limited depth (from a few cm to about 1.5 m), shallow landslides have been responsible for 50% of mass-movement casualties in the Piemonte region during the 20th century (Tiranti and Rabuffetti, 2010). The surprisingly high death tolls are likely due to the high velocity of landslides which often exceeds >5 m $s^{-1}$, their rapid evolution and as a result of the large number of phenomena that can be activated by a single rainfall event. Climate of the region is characterized by a bi-modal seasonal distribution of precipitation with maxima during spring and autumn and minima in summer and winter. In the Lago Maggiore area, mean annual precipitation is 2200–2400 mm, whereas only 650 mm are measured next to the Apennines.

Meteorological records from the wider Lago Maggiore region show a general increase in mean, maximum and minimum daily temperatures, and a sharp decrease of days with freezing (from 26 to 18 days $yr^{-1}$ in Oropa located at 1180 m asl) between the 1990 and 2000. Similarly, snow depths have increased for the months of November and December (Terzago et al., 2010) whereas snow cover depths and duration have decreased strongly at intermediate and high altitudes and in particular in spring. The observed decrease in summer precipitation and increase in winter precipitation is expected to continue in the future (Gobiet et al., in press). These seasonal changes in general and the expected associated shift in heavy precipitation events in particular are likely to have an impact on the temporal frequency, seasonality and severity of shallow landslides in the study region.

Observational data indicates significant changes in the frequency, seasonal distribution and number of landslide occurrences in the Piemonte region over the past decade. Fig. 9 shows that until 2002, shallow landslides were characterized by a high density of activations (generally >1000) during widespread, prolonged and often extreme autumn rainfalls. Between the early 1990s and the early 2000s, the mean interval between widespread landsliding was roughly one year. The landslide events of September and October 1993, November 1994, October 1996, November 1997, September 1998, October 1999, were also characterized by a high spatial density of shallow landslides (between 100 to 180 phenomena per $km^2$). The spatial density of landslides was similar during the events in June, October, and November 2000 (Ramasco and Susella, 2007), but the clustering is probably reflecting the persisting wet initial soil moisture conditions prevailing during that year. Since 2002, however, shallow landslides have been triggered in much smaller numbers and with a density of 10–30 slides per $km^2$. In addition, they were triggered by spring rainfalls of more moderate intensity. Such events have been recorded in March 2002, May 2002, June 2002, May 2004, May 2008, December 2008, April 2009, May 2010, June 2010, March 2011, and November 2011 (Tropeano et al., 2006; Tiranti et al., 2013).

The landslide events from December 2008 to April 2009 and the event of March 2011 are described in the following in more detail. These events are representative cases to illustrate the changes observed in landslide triggering since 2002. It is thought that these examples could represent first insights into what could become sustained changes in the overall frequency and severity of shallow landslide occurrences in the Piemonte region in a future greenhouse climate.

In winter 2008–2009, major snowfalls occurred very early and covered the region in snow in late October and again in late November, followed by heavy and widespread rainfalls between December 14 and 17. At elevations of up to 800 m asl, snow depth and cumulated fresh snowfall exceeded the maxima record in the historical dataset (1966–2005). Total precipitation measured during the four-day event was 252 mm in the hillslopes of Tertiary Piemonte Basin (TPB) and almost 400 mm in the Alps. This event triggered ca. 100 shallow landslides in the TPB and the Torino Hill (Fig. 10a). Snowfalls in January 2009 contributed further to the quite unusual snowpack at low elevations. Between March 28 and April 3, a Mediterranean storm released significant precipitation over the western Alps, adding an important layer (80–100 cm) to the pre-existing snow above 1500 m asl. Snowpack was continuous at elevations >1500 m asl and exceeded 200 cm at elevation of 2000 m asl, and exceeded the 90th percentile of historical data (Table 1) in many locations. Intense and widespread rainfalls

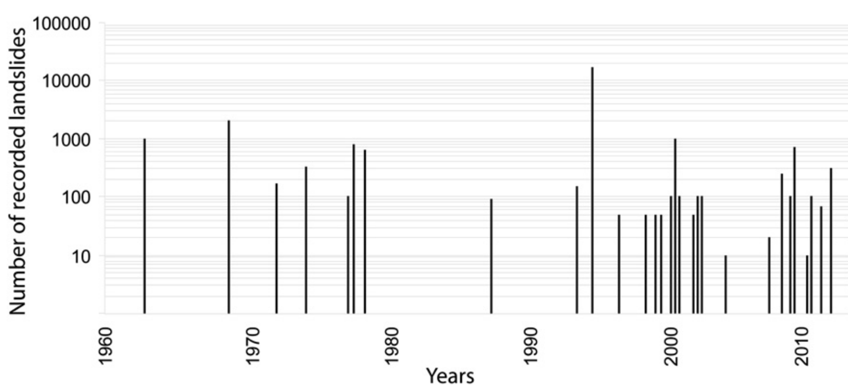


**Fig. 9.** Shallow landslide crises and number of landslides triggered between the 1960s and today. The landslide scale is logarithmic.

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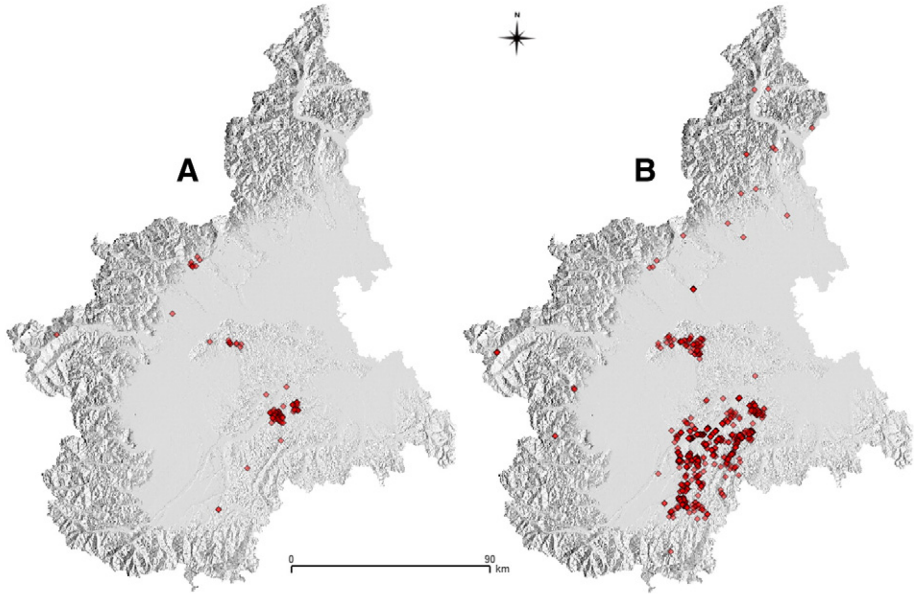


**Fig. 10.** Distribution of shallow landslides triggered in (A) December 2008 (total number of landslides n ~= 100) and in (B) April 2009 (n ~= 750).

between April 26 and 28, 2009 triggered roughly 750 shallow landslides in the TPB (Fig. 10b), in particular at elevations below 1300–1400 m asl, as well as significant floods along the main rivers, mostly in southern Piemonte. Rainfall duration between the two events in December 2008 and April 2009 was comparable, with slightly less precipitation during the spring storm (i.e. 228 mm in southern Piemonte, 364 mm in the Alps), but substantially more shallow landslides.

The abundant snowfalls in late autumn and winter 2008 represent an important contribution to ground water recharge because the first significant snowmelt in the area started at the time of the December 14–17, 2008 rainfalls. The addition of snowmelt to the rainfall certainly facilitated the triggering of shallow landslides. As illustrated in Fig. 11, an unusually important snowpack was measured in TPB in early February 2009. We estimate the snow water equivalent to ca. 100 mm which would have been made available in March 2009 and into April 2009, thus adding to the effect of the rainstorm in late April 2009. As a consequence, and despite the fact that the rainfall events of December 2008 and April 2009 were comparable in nature and intensity, moderately widespread landslide events were observed only on April, as the contribution of snow melt was quite irrelevant for landslide triggering and runoff in December due to the gradual melting of snow.

In winter 2010–2011, three important snowfall events hit the TPB. Snow accumulation on the ground was, however, rather limited because of rapid snow melt in the days after each event. Between March 14 and 16, 2011, widespread snowfalls affected the Piemonte region with precipitation of >200 mm in the Alps and 40–60 mm in the TPB.

**Table 1**
Comparison between snow cover on 28 February 2009 in the wider study area (obtained from snow gauge measurements) and historical reference values in the Alps.

| Sector of the Italian study region | Altitude | Snowpack [cm] | Historical value [cm] | |
|---|---|---|---|---|
| | | | 10th percentile | 90th percentile |
| Northern | 2000 m asl | 257 | 77 | 230 |
| | 1500 m asl | 144 | 32 | 145 |
| North-western | 2000 m asl | 205 | 30 | 215 |
| | 1500 m asl | 180 | 0 | 130 |
| Western | 2000 m asl | 193 | 37 | 168 |
| | 1500 m asl | 83 | 0 | 82 |
| Southern | 2000 m asl | 108 | 0 | 182 |
| | 1500 m asl | 163 | 0 | 85 |

Snow limit was unusually low for the season at about 600 m asl. Due to a sudden temperature increase at the end of the precipitation episode, snowmelt was almost instantaneous, notably in the TPB area, thereby enhancing the effects of rainfall. Landslides were observed in the entire area, but the largest number of shallow landslides (ca. 150) occurred again in the hillslopes of TPB (Fig. 12).

Table 2 compares the landslides of 2008, 2009 and 2011 with the largest historical event of the TPB in fall 1994, and points to the effects of ongoing climatic change on the seasonality and drivers of landslide activity in the Piemonte region in general and in TPB in particular. In contrast to the disasters of 1994, where snow did not play a role, we observe that a vast majority of landslide events of the early 21st century were clearly triggered by rainfall and the contribution of snowmelt. In the literature, the triggering of shallow landslides has been ascribed to rainfalls (Caine, 1980; Aleotti, 2004; Guzzetti et al., 2008), whereas antecedent precipitation has been neglected. In the present case, however, triggering of a notable number of shallow winter and spring landslides cannot be attributed to the moderate rainfalls alone, but to the additional contribution of snowmelt. It also seems that the sedimentary rocks of TPB, with alternating thin strata of different permeability and multi-confined aquifers systems, may exfiltrate significant amounts of antecedent infiltrated snowmelt water during a rainfall event, therefore rendering groundwater a decisive predisposing factor, even for the triggering of shallow landslides.

Based on statistically downscaled RCM data (REMO, RegCM3) with a horizontal resolution of $10 \times 10$ km$^2$ and using the IPCC A1B scenario (Gobiet et al., in press), the Piemonte region and TBP will face a warming up to 2 °C until 2050, mostly above 1500 m asl in fall, as well as an increase winter precipitation, and dryer conditions in spring and summer. Above 1500 m asl, a strong decrease in snow cover is projected for future winters and springs. Consequences of projected climatic changes are already somewhat discernible in recent changes in frequency, number and seasonality of landslide activity in the northwestern Alpine region, especially at altitudes below 1500 m. Similar to the French Alps (Lopez Saez et al., 2013a), snowmelt has also become an important predisposing factor of landslide triggering in the Piemonte since the very early 21st century. Since 2002, landslides have been observed to not only occur more frequently in early spring and tend to be triggered by moderate rainfalls, but also occur in smaller numbers. It thus seems likely that the expected climatic changes will lead to more frequent spring landsliding in the region, but that individual

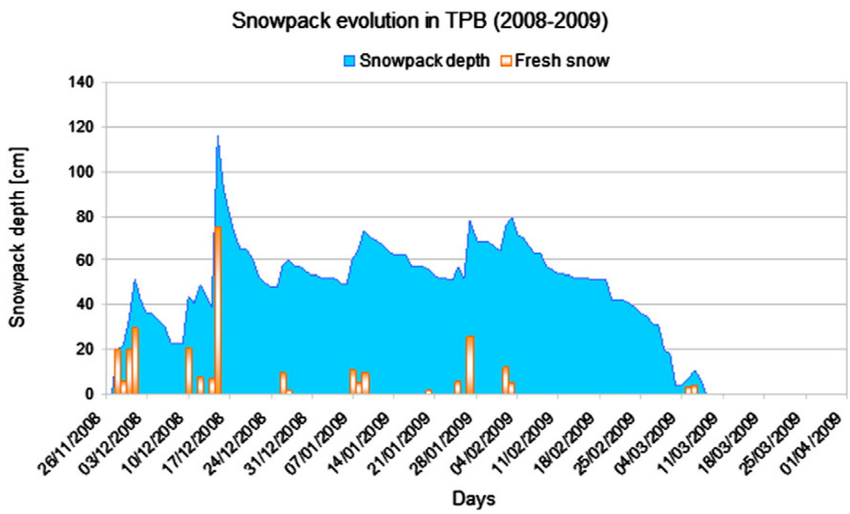


**Fig. 11.** Snow depth evolution in the hillslopes of the Tertiary Piemonte Basin (TPB) during winter 2008–2009 and spring 2009. The snowmelt in April 2009 has led to the release of 750 shallow landslides in the region.

landslide episodes will possibly trigger fewer events. On the contrary, and in line with recent observations, fall events, characterized by a large spatial density of landslide occurrences, might become increasingly scarce.

## 5. Conclusions

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) states that the number of warm days has increased globally, and that heat waves and heavy precipitation events have increased in Europe since 1950 (IPCC, 2013). In high-mountain regions, the evolution of mean and extreme temperatures is comparable and will most likely increase further over the next decades. Along with the projected changes of temperatures and precipitation, the temporal occurrence and size of mass movement phenomena will likely be altered as well. In this study, mainly based on recently published research, we have illustrated cases of debris flows, rockfalls and landslides from several mountain environments to illustrate climate change impacts on these processes. Current understanding suggests that only moderate changes in the overall frequency of high-elevation debris-flow events from permafrost environments will occur over the short term, but an increase in the overall magnitude of debris flows due to larger amounts of sediment delivered to the channels and an increase in extreme precipitation events is possible. Locally, however, strong and unprecedented changes in frequency and magnitude of debris flows have recently been observed in relation with complex process coupling, associated with combined changes in climate, glacier, permafrost and sediment availability. Such local exacerbations of general trends are likely to be observed in the future as well. More generally, the absolute number of days with conditions favorable for the release of debris flows will likely decrease, especially in summer, and the anticipated increase of rainfalls during the shoulder seasons (March, April, November, December) is not expected to compensate for the decrease in future heavy summer rainfalls. The volume of entrained debris will crucially depend on the stability and/or accelerations of rock glacier bodies. Such rock glacier instabilities are expected to lead to debris flows without historic precedents in the future. Several lines of arguments also suggest a further increase in frequency of rock slope failures. Recent progress in observations, modeling and physical understanding indicate that excessively warm air temperatures, glacier shrinkage and downwasting, as well as permafrost warming and thawing will affect and reduce rock slope stability in the direction that adversely affects rock slope stability. Changes in landslide activity in the Alps are likely to be related to elevation. Above 1500 m asl, the projected decrease in snowpack and duration in future winters and springs will probably

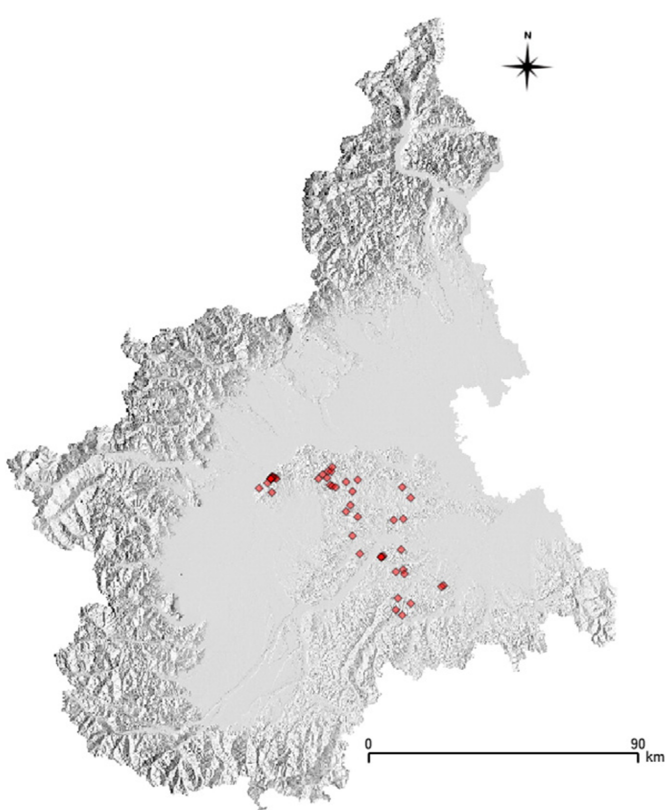


**Fig. 12.** Distribution of shallow landslides triggered in March 2011 (total number of landslides n ~= 150).

**Table 2**
Comparison of recent winter and/or spring landslides and historical fall landslides in the tertiary Piemonte Basin (TPB).

| Landslide event | Rainfall value [mm] | SWE contribution [mm] | shallow landslides in TPB |
|---|---|---|---|
| November 1994 | 330 | 0 | >10,000 |
| December 2008 | 114 | <10 | 100 |
| April 2009 | 120 | 100 | 750 |
| March 2011 | 60 | 70 | 150 |

affect the frequency, number and seasonality of landslide activations. In the French Alps and the Piemonte region, 21st century landslides have been demonstrated to occur more frequently in early spring and tend to be triggered by moderate rainfalls, but also to occur in smaller numbers. On the contrary, and in line with recent observations, events in autumn, characterized by a large spatial density of landslide occurrences, might become increasingly scarce.

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