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Debris-flow activity in the Ritigraben torrent (Valais Alps, Switzerland): Will there be less but bigger events in a future greenhouse climate?

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ABSTRACT: Tree-ring records and climate proxies suggest that cool summers with frequent snowfalls regularly prevented the release of debris flows at Ritigraben between the 1570s and 1860s, whereas the warming trend in conjunction with greater precipitation totals in summers and falls apparently led to an increase in activity between 1864 and 1895 and in the early 20th century. Simultaneously, the seasonality of events started to shift from June and July to August and September. Given that RCMs project extreme precipitation events to occur less frequently in summer and that wet spells will become more common in spring or fall, it is conceivable that debris flows will not necessarily occur as frequently in the future as they did in the past. But even if the frequency of events is likely to decrease, the magnitude of summertime debris flows and related impacts could be greater than currently.

1 INTRODUCTION

In the recent past, the Swiss Alps have experienced several events of extreme precipitation conditions that have led to widespread flooding and debris-flow activity, severe damage to infrastructure and fatalities on cones or at the mouth of gullies (Rickenmann & Zimmermann 1993, BWG 2002, Schmidli & Frei 2005, Beniston 2006). With the projected changes of the climate and global warming (Christensen & Christensen in press), there is much debate about modifications in the amount, intensity, duration, type and timing of precipitation events as well as about their effect on related flooding, debris-flow and other mass-wasting processes (e.g., Bradzil et al. 2002, Milly et al. 2002, Mudelsee et al. 2003). Consequently, a plethora of climatological and hydrological scenarios have been developed to seize potential impacts of future greenhouse climates, but Goudie (2006) pertinently emphasizes that these scenarios have not been matched for the most part by the development of scenarios of future changes in geomorphological systems.

Previous studies focusing on future changes have mainly been based on data of past debris-flow events covering, at best, parts of the 20th century or on comparably short time series of meteorological records. For instance, Rebetez et al. (1997) compared archival records on debris flows with meteorological data and identified an increase in the occurrence of large debris flows in the Swiss Alps since the 1980s. Marchi & Tecca (2006) identified more records on debris flows in historical documents for the last decades as well. They conclude that the larger number of events could be due both to an increase in the frequency and to a larger availability of information. In the French Alps, Van Steijn (1996) reported high debris-flow activity since the 1980s, but there does not seem to exist a univocal increase in the frequency of debris-flow events as a result of climatic change (Jomelli et al. 2004, in press).

As studies focusing on the role of (changing) climatic conditions on the release of debris flows remain scarce and widely limited by the paucity of data on past events or triggering weather conditions, there is an inherent need to further examine the natural variability of extreme weather events and to gather detailed information on past debris-flow activity before stating any cause-to-effect relationship between the projected global warming and the incidence of geomorphic processes.

On forested cones, data on past debris-flow activity can be considerably improved by means of dendrogeomophological analysis of trees disturbed by former events. In the past, spatial patterns of debris-flow events have been assessed through the coupling of geomorphic with tree-ring data (Stoffel et al. 2006, Bollschweiler & Stoffel in press, Bollschweiler et al. in press). Similarly, growth anomalies in tree-ring records have been used to estimate the magnitude of former events (Strunk 1997, Baumann & Kaiser 1999).

The purpose of this paper is to assess the debris flow activity and process dynamics in an ephemeral torrent originating from a periglacial environment in the Valais Alps (Switzerland). Through the analysis of 2450 tree-ring records obtained from 1204 trees disturbed by past debris flows, we (i) investigate the frequency and seasonality of events and (ii) discuss potential feedbacks of the debris-flow system to the projected changes in precipitation in a future greenhouse climate.

2 STUDY SITE

The analysis of past debris-flow dynamics and growth disturbances in century-old trees was conducted at the Ritigraben torrent (Switzerland, 46° 11' N, 7° 49' E). Figure 1 illustrates the torrent taking its source at approximately 2,600 m a.s.l. In the departure zone, geophysical prospecting indicates the existence of contemporary permafrost (Lugon & Monbaron 1998).

On its downward course to the Mattervispa river, the torrent passes a large forested cone (32 ha) on a structural terrace (1,500–1,800 m a.s.l.), where debris-flow material affects trees within an old-growth stand composed of European larch (*Larix decidua* Mill.), Norway spruce (*Picea abies* (L.) Karst.) and Swiss stone pine (*Pinus cembra* ssp. sibirica). At the confluence of the Ritigraben torrent with the receiving Mattervispa River at 1,080 m a.s.l., depositional forms are lacking and material is immediately eroded.

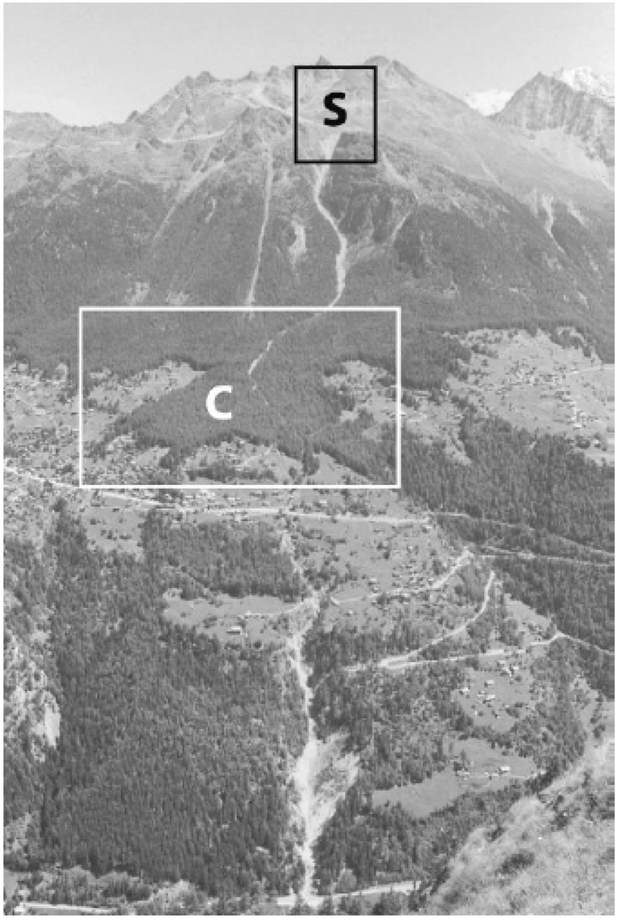

Figure 1. The Ritigraben torrent (Swiss Alps) takes its source (S) at 2,600 m a.s.l. and passes through a forested cone (C), before it converges with the Mattervispa river (1,080 m a.s.l.).

Debris-flow material consists of heavily disintegrated, weathered metamorphic granites of Permian age (Labhart 2004) and mainly originates from the steep departure zone of the Ritigraben torrent, where an active rock glacier provides material for the initiation of debris-flow events. Further debris is mobilised from the channel, which is continuously recharged with fallen rocks or through lateral channel erosion. While mean rock sizes on the cone surface generally remain well below 2 m in diameter, there is also evidence that boulders with volumes exceeding 10 m^3 have been transported by debris flows in the past.

The high elevation of the source area currently restricts debris-flow activity in the Ritigraben torrent from June to September (Stoffel et al. 2005a). Present-day debris flow activity is initiated primarily by persistent precipitation in fall rather than thunderstorms in summer. The documentation of past events only covers the last two decades (1987–2007) and the "largest event ever" was recorded in 1993 with eleven erosive surges and a volume estimated to 60,000 m^3 (Zimmermann et al. 1997).

3 MATERIAL AND METHODS

On the intermediate debris-flow cone, a majority of the century-old conifers (*Larix decidua*, *Picea abies*, *Pinus cembra*) show visible growth defects related to past debris-flow activity (i.e. tilted stems, partial burying of the trunk, decapitation, destruction or erosion of roots, visible scars). Based on a detailed geomorphic map and on an outer inspection of the stem surface, trees were sampled that have obviously been disturbed by past debris flows.

In the field, at least two cores were extracted per tree using increment borers, one core in the flow direction of past debris flows and another core on the opposite side of the trunk (max. length of cores: 40 cm, Ø 6 mm). In order to gather the greatest amount of data on the growth disturbances caused by past events, increment cores were preferably sampled at the height of the visible damage or within the segment of the stem tilted during past events. In the case of visible scars, further increment cores were extracted from the callus tissue overgrowing the wound.

In addition to the disturbed trees sampled on the cone, we selected undisturbed reference trees from a forest stand located southwest of the cone. For every single reference tree, two cores per tree were extracted perpendicularly to the slope. In contrast to the disturbed trees, increment cores of the reference trees were extracted at breast height ($\approx$130 cm).

In total, 1204 trees were sampled (2450 increment cores): 539 *Larix decidua*, 429 *Picea abies* and 134 *Pinus cembra* trees (2246 cores) from the debris-flow cone as well as 102 trees (204 cores) of the same species from undisturbed reference sites.

In the laboratory, samples were analyzed and data processed following the standard procedures described in Bräker (2002). Single steps of sample analysis included surface preparation, counting of tree rings, skeleton plots as well as ring-width measurements using digital LINTAB positioning tables connected to a Leica stereomicroscope and TSAP 3.0 software (Time Series Analysis and Presentation, Rinntech 2007). Growth curves of the disturbed samples were then crossdated with the corresponding reference chronology constructed from undisturbed trees for each of three conifer species sampled on the cone, in order to separate insect attacks or climatically driven fluctuations in tree growth on the study area from growth disturbances caused by debris flows (Cook & Kairiukstis 1990).

Growth curves were then used to determine the initiation of abrupt growth reduction or recovery (Schweingruber 2001, McAuliffe et al. 2006). In the case of tilted stems, both the appearance of the cells (i.e. structure of the reaction wood cells) and the growth curve data were analyzed (e.g., Braam et al. 1987, Fantucci & Sorriso-Valvo 1999).

Finally, the cores were visually inspected so as to identify further signs of past debris-flow activity in the form of callus tissue overgrowing abrasion scars or tangential rows of traumatic resin ducts formed from cambium damage (Stoffel et al. 2005b, 2006, Perret et al. 2006).

As conifer trees react immediately to damage with the formation of callus tissue or tangential rows of traumatic resin ducts, the intra-annual position of growth disturbances was further used to assess the moment of debris-flow activity in particular years with monthly precision (Stoffel et al. 2005c, Stoffel & Beniston 2006, Stoffel in press). Our tree-ring based data on the intra-seasonal timing of debris flow events were then compared with records from a local meteorological station, operational since 1863 and with archival data on flooding in rivers of the Valais Alps (Lütschg-Lötscher 1926, Röthlisberger 1991).

4 RESULTS

Data on the innermost rings of the 1102 *Larix decidua*, *Picea abies* and *Pinus cembra* trees sampled on the cone varied from AD 1492 to 1962 with 53% of the increment cores showing more than 300 tree rings at sampling height and old trees being quite evenly spread over the cone. The youngest trees, in contrast, are most commonly found near the forest fringe, where anthropogenic interventions influence the age and succession rates of trees (i.e. farming activities, extraction of fire- and construction wood).

Analysis of the disturbed trees allowed reconstruction of 2263 growth disturbances caused by passing debris-flow surges or the deposition of material on the cone. Table 1 shows that signatures of past events were mainly identified on the increment cores via tangential rows of traumatic resin ducts or reaction wood. Abrupt growth recovery or reductions were only occasionally found in the tree-ring series and wounds and overgrowing callus tissue was rarely present on the cores.

In total, dendrogeomorphological analysis of the increment cores allowed reconstruction of 123 debris-flow events covering the last 440 years. The reconstructed frequency of debris flows is given in Figure 2. From the data, it appears that periods of repeated debris-flow activity alter with phases of little or no activity. Such clustering of events is especially obvious in the early 1870s, the 1890s or between the late 1910s and 1935.

In Figure 3, the reconstructed frequency is broken down into 10-yr periods, with bars representing variations from the mean decadal frequency of debris flows for the period 1706–2005, when 3.26 events occurred every ten years. Results illustrate that the frequency of events generally remained well below average during most of the classical "Little Ice Age" (1570–1900; see Grove, 2004) and that periods with increased debris-flow activity only start to emerge after the last "Little Ice Age" glacier advance in the 1860s. This period of increased activity continued well into the early 20th century and culminated between 1916 and 1935. During these 20 years, 14 events were derived from the tree-ring series. Results further illustrate that this episode of important activity was followed by a decrease in debris-flow activity. In a similar way, very

Table 1. Relative number of growth disturbances used to infer past debris-flow activity from increment cores.

Growth disturbance	Absolute number	%
TRD*	987	43.6
Injuries	118	5.2
Callus tissue	22	1.0
Reaction wood	728	32.1
Growth reduction	194	8.6
Growth release	214	9.5
Total	**2263**	**100.0**

* TRD = tangential row of traumatic resin ducts.

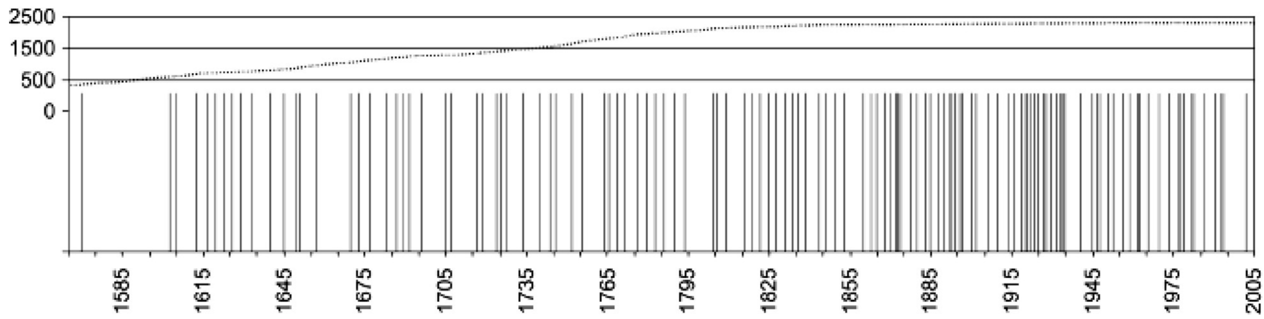

Figure 2. Tree-ring based reconstruction of debris flow activity at Ritigraben between AD 1566 and 2005 containing 123 events. The sample depth gives the number of cores available for analysis at specific years in the past (modified after Stoffel et al, in press).

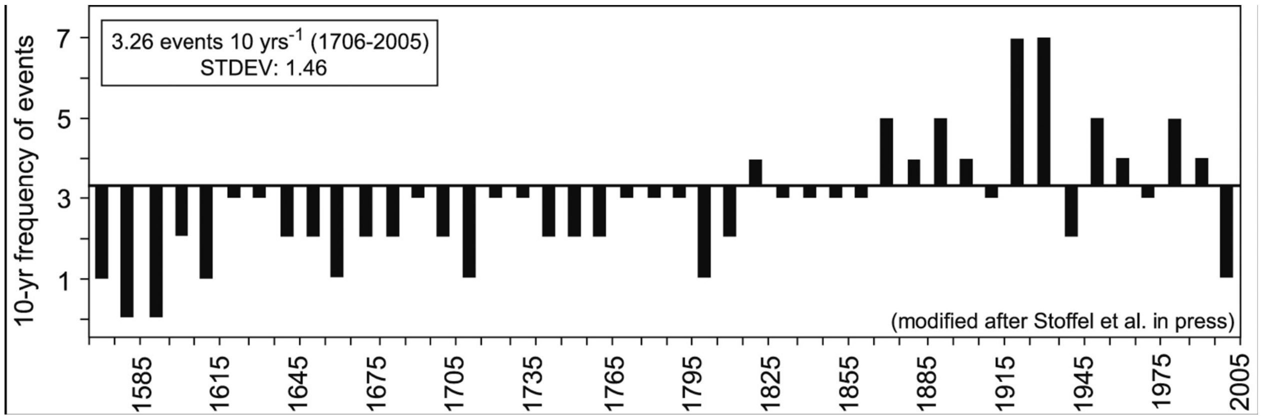

Figure 3. Reconstructed 10-yr frequencies of debris-flow events for the period AD 1566–2005. Results are presented as variations from the mean decadal frequency of debris flows of the last 300 years (AD 1706–2005).

low activity can be observed for the last 10-yr segment (1996–2005) with only one debris-flow event recorded on August 27, 2002. Along with the 10-yr segments of 1706–1715 and 1796–1805, the most recent ten years exhibit the lowest debris-flow activity in the last 300 years.

The seasonality of past events was assessed based on the intra-annual position of tangential rows of traumatic resin ducts in the tree rings, archival data on flooding in rivers of the Valais Alps as well as on meteorological records of the local MeteoSwiss station (1863–2005). Results on the seasonality of debris-flow activity are presented in Figure 4, indicating that events generally occurred much earlier in the summer prior to 1900.

This is especially true for the period 1850–1899, when more than 70% of the reconstructed debris flow events took place in June and July and no incidence in September. In the 20th century, debris-flow activity clearly shifted towards August and September, with not a single event registered for June after AD 1962.

Based on our reconstructions, it also appears that snowfalls and frozen ground apparently inhibit debris entrainment from the starting zone (>2,600 m a.s.l.) during precipitation events between October and May.

5 DISCUSSION

In the study we report here, increment cores extracted from 1102 living *Larix decidua* Mill. *Picea abies* (L.) Karst. and *Pinus cembra* ssp. sibirica trees allowed reconstruction of 2263 growth disturbances belonging to 123 debris-flow events since AD 1566.

On the basis of the evidence presented above, it is possible to characterize climatological as well as meteorological factors driving debris-flow activity in the case-study area. Tree-ring based records of past debris-flow activity suggest that comparably cool summers with frequent snowfalls at higher elevations regularly prevented the release of debris flows most of the time between the 1570s and 1860s. The warming trend in conjunction with greater precipitation totals in summers and falls between 1864 and 1895 did, in contrast, lead to an increase of meteorological conditions favourable for the release of debris flows from the departure zone. Enhanced debris flow activity continued well into the 20th century and the reconstruction exhibits a clustering of events for the period 1916–1935, when warm-wet conditions prevailed during summers in the Swiss Alps (Pfister 1999).

The reconstructed frequency is also in agreement with chronicle data on flooding events in Alpine rivers

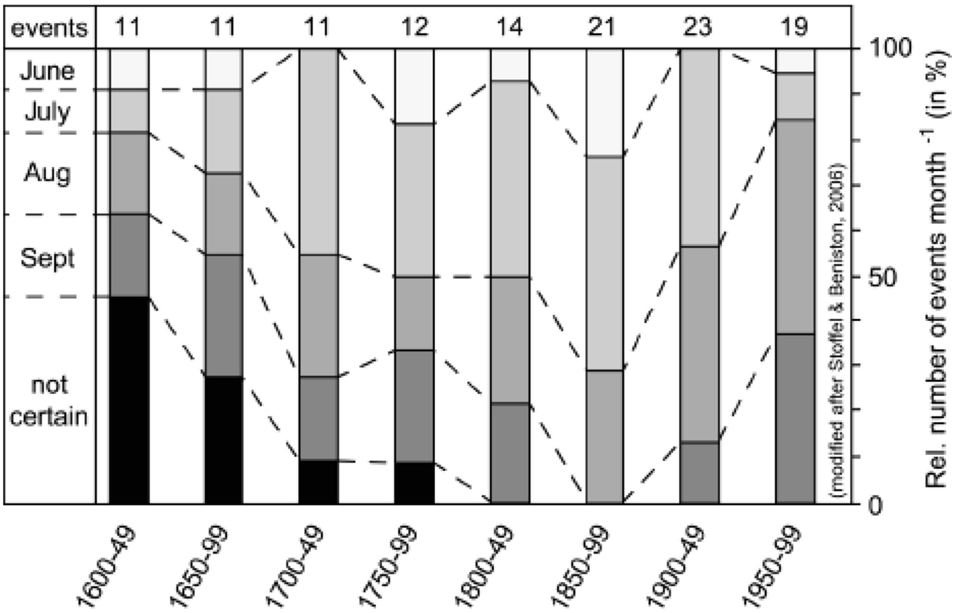

Figure 4. Seasonality of past debris-flow activity as inferred from the intra-annual position of tangential rows of traumatic resin ducts in the tree ring, archival data on flooding as well as meteorological data (1863–2005).

of Switzerland (Lütschg-Lötscher 1926, Röthlisberger 1991), where a scarcity of flooding events are observed for most of the "Little Ice Age" and during the mid-20th century as well. However, it is worthwhile to note that floods in adjacent Alpine rivers became more frequent in the 1830s (Pfister 1999), which is three decades before activity increased in the investigated case-study area. The reasons for this time lag have not been analyzed in details, but it can be assumed that they are due to the comparably cool temperatures that prevailed at high elevation sites during this period.

The seasonality of events underwent changes over the period covered by the reconstruction as well. Based on the tree-ring record, we observe a shift in the debris-flow activity from June and July to August and September over the 20th century, with not a single event registered for June after AD 1962. A comparison of reconstructed debris-flow events with archival data on flooding in adjacent rivers further indicates that convectional rainfalls in summer (i.e. local thunderstorms) would have preferentially triggered debris flows from the 1860s until the 1980s. In contrast, cyclonic rainstorms affecting large parts of the Alps in late summer and early autumn have apparently become more frequent since the 1980s and are responsible for the debris-flow events of 1987, 1993 and 1994. While yet another cyclonic rainstorm caused considerable damage in rivers neighbouring the case-study site in October 2000, frozen ground and snowfalls inhibited excessive runoff and debris entrainment from the starting zone of the Ritigraben located at >2,600 m a.s.l. (Bardou & Delaloye 2004).

The reconstructed shift of debris-flow activity from June and July to August and September can be further

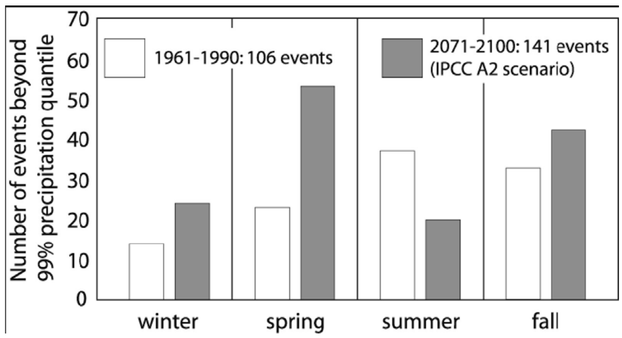

Figure 5. Number of heavy precipitation events beyond the 99% quantile in the Swiss Alps (corresponding to just over 60 mm/day) under current (1961–1990) and a future greenhouse climate (2071–2100) based on the IPCC A2 Scenario (modified after Stoffel & Beniston 2006).

explained by the negative trend observed for heavy summer rainfall and the slightly positive trend found in heavy fall precipitation intensities in the study region over the 20th century (Schmidli & Frei 2005).

Despite uncertainties related to regional climate simulations of precipitation in complex terrain, recent work by Beniston (2006) based on 4 regional model projections for a "greenhouse climate" by 2100 suggests that mean and extreme precipitation may undergo a seasonal shift, with more spring and fall heavy precipitation events (defined as the 99% quantile values of daily precipitation, which corresponds to just over 60 mm/day) than currently, and less in summer.

Figure 5 illustrates the seasonal shift in the occurrence of heavy precipitation events in the Swiss Alps as discussed by Beniston (2006), for current climate (1961–1990 reference period) and a greenhouse climate for 2071–2100 based on the IPCC (International Panel on Climate Change) A2 greenhouse-gas emissions scenario (Nakićenović et al. 2000). The histograms are based on the HIRHAM regional climate model (Christensen et al. 1998), one of a number of models applied to climatic change studies in Europe in the context of the EUPRUDENCE project (Prudence 2007, Christensen & Christensen in press). This increase in the number of extreme precipitation events (i.e. over 30% between the two periods) supports earlier findings by Frei et al. (1998).

Paradoxically, the impacts associated with future extreme rainfall on debris-flow torrents originating at high elevations may be even reduced. This is because spring and autumn temperatures are suggested to remain 4–7°C degrees below current summer temperatures in a future greenhouse climate, implying lower freezing levels in future springs and autumns as compared to current summers and therefore probably widespread buffering effects of snow on runoff and debris entrainment. Given that mean and extreme precipitation events are projected to occur less frequently in summer and that wet spells will become more common in spring or fall, it is conceivable that debris flows will not necessarily occur as frequently in the future as they did in the past in the case-study area.

However, even if the frequency of summer events is likely to decrease in a future greenhouse climate, the magnitude of future summertime debris flows and related impacts could (theoretically) be greater than currently. This is because warmer temperatures and higher precipitation intensities could result in larger runoff, more important transport capacity of surges and a bigger erosive potential of debris flows.

However, the release of debris-flow surges and the ensuing magnitude of events not only depend on precipitation intensities, their duration and subsequent runoff, but also on sediment availability in the starting zone as well as in the debris-flow channel. After the high-magnitude event in September 1993, when eleven surges mobilized an estimated volume of 60,000 m^3 (Zimmermann et al. 1997), the main channel was almost immediately recharged with debris due to instabilities in and partial collapses of the oversteepened lateral walls, allowing new debris flow activity only one year after the big 1993 event (Bloetzer et al. 1998). Based on observations in the field, we believe that as little as 10% of the debris flow volume reaching the Mattervispa River would actually start directly from the starting zone and that up to 90% of the material would be mobilized from the huge unconsolidated moraine and debris deposits along the flow path of the Ritigraben torrent. It can therefore be concluded that debris is readily available and easily entrained along the debris-flow channel and cannot be considered a limiting factor.

Debris availability and recharge rates could, in contrast, undergo changes in the departure zone due to changes in climatic conditions. Given that temperatures will rise by several degrees in a future greenhouse climate (according to e.g., the IPCC A2 scenario, see Nakićenović et al. 2000), it is conceivable that this will have consequences on the currently prevalent permafrost as well as on the dynamics of the active rock glacier that nowadays feeds the starting zone of debris flows with material. Preliminary results from borehole temperature measurements realised next to the departure zone of the Ritigraben torrent suggest that permafrost is comparably temperate and possibly in an unstable state (Herz et al. 2003). At other locations in the Swiss Alps (Roer et al. 2005, Delaloye pers. comm.), important accelerations have been observed in rock glacier movements ("surges") over the last few decades. It is, thus, possible that rock glacier movements could increase at our study site in the future as well and therefore deliver more debris to the starting zone of debris flows in the Ritigraben torrent. In conjunction with more precipitation events >60 mm/day, these larger amounts of debris could theoretically lead to the entrainment of more material and subsequently to larger debris flows in the system.

On the other hand, should the ice once completely disappear from the rock-glacier body at Ritigraben, one could also imagine that debris would less easily be transported to the starting zone of debris flows and therefore less material be available for the initiation of future events.

The above considerations on potential changes in the seasonality of heavy precipitation events and on potential modifications of rock-glacier dynamics remain highly speculative for the moment. Nonetheless, local authorities should not wait with the planning of appropriate constructive measures so as to (better) protect the buildings located along the currently used channel as well as on the intermediate debris-flow cone from future damage. Regardless of expected changes in the frequency or magnitude of debris-flow events at Ritigraben, they have to be aware that considerably large debris-flow events have repeatedly occurred in the past, and that they will occur in the future as well. As the lateral walls of the currently used channel (that have been incised by the September 1993 event) already started to collapse, it is possible that future debris flows could overtop the channel above 1,650 m a.s.l., reactivate abandoned flow paths and deposit material in the eastern or south-western parts of the cone, theoretically threatening buildings and public infrastructure.

6 CONCLUSIONS

The analysis of 2450 tree-ring sequences from 1102 disturbed conifer trees provided an unusually complete record on past debris-flow activity in a torrent originating from permafrost environments. Reconstructions indicate that debris flow activity remained comparably low during most of the "Little Ice Age" and that high activity culminated in the early 20th century (1916–1935). More recently, debris-flow activity became less frequent and the projected shift of heavy precipitation events (over 60 mm/day) from summer to spring and fall could cause the frequency to remain at this below-average level in the long term. But even if the frequency of summer events is likely to decrease in a future climate, the magnitude of future summertime debris flows and related impacts could probably be greater than currently. This is because warmer temperatures and higher precipitation intensities could result in larger runoff, more important transport capacity of surges and a bigger erosive potential of debris flows. Irrespective of changes in the frequency or magnitude of debris-flow events, local authorities should realize appropriate constructive measures along the channel and on the intermediate cone so as to prevent damage to buildings and other infrastructure.

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