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On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: A case study from the Swiss Alps

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[1] Tree-ring based reconstructions of 123 debris-flow events in a case-study area of the Swiss Alps since AD 1570 show enhanced activity during the wet periods (1864–1895) following the last LIA glacier advance and in the early decades of the 20th century. In contrast, comparably low activity can be observed since 1995, with only one event recorded. From the reconstructions and based on RCM simulations, there are indications that debris-flow frequencies might continue to decrease in a future climate, as precipitation events are projected to occur less frequently in summer but become more common in spring or fall.

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1. Introduction

[2] The adverse climatic conditions and the glacierization processes of the Little Ice Age (LIA) are particularly well represented in the geomorphological record of the Swiss Alps by moraine systems and other glacial landforms [*Maisch et al.*, 1999]. The history of advance and retreat of outlet glaciers has extensively been studied in the past, indicating several strong glacier surges during the LIA with peaks in the Valais Alps around 1370, in the 1670s and 1680s as well as in the 1860s [*Zumbühl and Holzhauser*, 1988].

[3] Simultaneously, this period also saw significant geomorphological activity and the formation of a range of non-glacial landforms. In northern Europe, climate during the LIA lead to an increase in the incidence of slope instabilities [e.g., *Blikra and Selvik*, 1998]. In the Swiss Alps, in contrast, there is almost no data available on gravity-driven processes during the LIA.

[4] This paper thus aims to assess the debris-flow activity in a catchment of the Swiss Alps during the period 1570–1900 (the classic LIA [see *Grove*, 2004]), to document its evolution in the 20th century and to give an insight as to possible changes in the 21st century. Through the analysis of 2246 tree-ring series obtained from 1102 conifers growing on a debris-flow cone, this study focuses on (i) the reconstruction of events with dendrogeomorphological methods, (ii) past and contemporary changes in the frequency and seasonality of events as well as on (iii) potential future debris-flow incidence in a torrent that originates within periglacial environments.

[5] The case-study area chosen for the analysis of past and present-day debris-flow activity is the Ritigraben torrent (Valais, Swiss Alps, 46°11′N, 7°49′E). In the source area of the torrent (2,600–3,214 m a.s.l.), contemporary permafrost was prospected with geophysical investigations. On its downward course to the Mattervispa river, the torrent passes a forested cone 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). Figure 1 provides an overview of the catchment and the intermediate cone. Previous investigations have shown that debris-flow activity in the torrent is restricted to June through September [*Stoffel et al.*, 2005a] and that the "largest event ever" occurred in 1993 with eleven surges and an estimated volume of *c.* 60,000 m^3 [*Zimmermann et al.*, 1997].

2. Material and Methods

[6] Records derived from trees growing in temperate regions provide annually-resolved data on past geomorphic

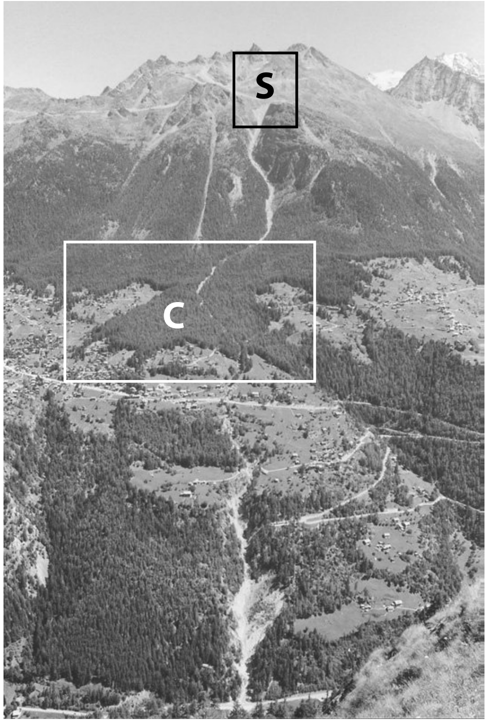

Figure 1. Photo of the investigated site in the Valais Alps, Switzerland. The Ritigraben torrent takes its source (S) at 2600 m a.s.l., passes through a forested cone (C), before converging with the main Mattervispa river.

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Table 1. Debris-Flow Signatures Identified in the 2246 Increment Cores Analyzed[a]

Signature	Number	%
TRD	987	43.6
Wound	118	5.2
Callus tissue	22	1.0
Reaction wood	728	32.1
Growth reduction	194	8.6
Growth increase	214	9.5
Total	2263	100.0

[a] TRD = rows of traumatic resin ducts.

processes that span several centuries, thus allowing assessment and dating of events prior to instrumental and historical records. The investigation of past debris-flow activity at Ritigraben was therefore based on 1102 *Larix decidua*, *Picea abies* and *Pinus cembra* trees (2246 cores) that have obviously been disturbed by events in the past. At least two cores per tree were extracted using increment borers, one in the flow direction of past debris flows and another on the opposite side of the trunk. In the case of visible scars, further cores were extracted from the wound and the overgrowing callus. In addition to the affected trees sampled on the cone, we selected 102 undisturbed reference trees from stands located next to the cone so as to separate insect infestations or climatically driven fluctuations in tree growth from disturbances caused by debris flows [*Cook and Kairiukstis*, 1990].

[7] Ring-width series and the visual inspection of samples were then used to assess abrupt growth reductions after stem burial or root exposure [*Schweingruber*, 1996], the onset of reaction wood after tilting [*Fantucci and Sorriso-Valvo*, 1999], the presence of callus tissue overgrowing abrasion scars or rows of traumatic resin ducts (TRD) resulting from cambium damage [*Stoffel et al.*, 2005b]. The identification of past events was based on the number of samples simultaneously showing a growth disturbance as well as on their spatial distribution. As conifers react immediately to damage with the formation of TRD [e.g., *Martin et al.*, 2002], the intra-annual position of the disturbance was further used to assess the moment of debris-flow activity in particular years with monthly precision [*Stoffel et al.*, 2006].

3. Results

[8] Analysis of the disturbed trees allowed reconstruction of 2263 characteristic growth disturbances caused by passing debris-flow surges or the deposition of material on the cone (Table 1). Signatures of past events were mainly identified on the increment cores via TRD (43.6%) or reaction wood (32.1%). Abrupt growth reductions or recovery were only occasionally found in the tree-ring series and wounds or overgrowing callus tissue were rarely present on the cores. In total, the analysis of signatures occurring simultaneously in different trees on the cone allowed the reconstruction of 123 debris-flow events covering the last 440 yrs. Figure 2 gives the reconstructed frequency of debris flows between AD 1566 and 2005.

[9] The innermost rings of living trees sampled on the cone ranged from 1962 to 1492, with 53% of the cores showing ≥300 rings at sampling height and old trees being quite evenly spread over the cone. It can thus be assumed that signatures of most events of the last 300 yrs have been recorded in the large number of samples used for the reconstruction. Prior to this period, the decreasing number of trees available for analysis may influence the quality of the reconstructed frequency.

[10] Figure 3 breaks the reconstructed frequency down into 10-yr periods, with bars representing variations from the mean decadal frequency of debris flows for the period 1706–2005 (i.e., 3.26 events 10 yr^{-1}). Results illustrate that decadal frequencies generally remained well below average during most of the LIA and periods with considerable above-average debris-flow activity only start to emerge from the data in the 1860s. Largely increased activity continued well into the early 20th century and culminated in two 10-yr periods between 1916 and 1935, when seven events each were derived from the tree-ring series. Results further show that this episode of important activity was followed by a rather sharp decrease in the 10-yr frequencies. In a similar way, very 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 periods of 1706–1715 and 1796–1805, the most recent ten years exhibit the lowest debris-flow activity in the last 300 yrs.

[11] The reconstructed frequency is in agreement with chronicle data on extreme flooding events in Alpine rivers of Switzerland [*Pfister*, 1999], where a scarcity of flooding events can be observed for most of the LIA and the mid 20th century as well. In contrast, floods in Alpine rivers started to become more frequent around the 1830s, i.e., almost three decades before activity increased in the investigated Ritigraben case-study area.

[12] Figure 4 illustrates the seasonality of past events based on the intra-annual position of wounds and TRD within the tree rings. Generally, debris flows 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 occurred in September. In the 20th century, debris-flow activity clearly shifted toward August

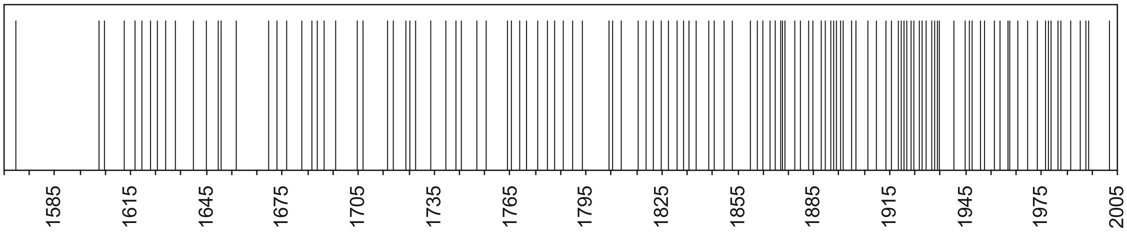

Figure 2. Tree-ring based reconstruction of debris flow activity at Ritigraben between AD 1566 and 2005.

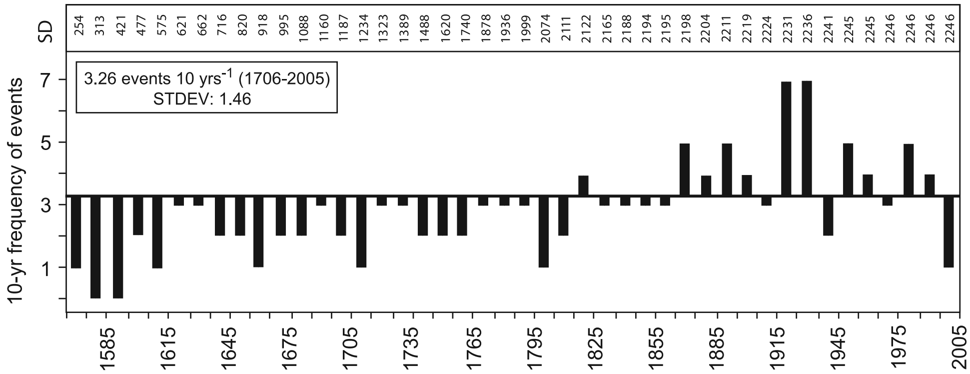

Figure 3. Reconstructed 10-yr frequencies of debris-flow events between AD 1566 and 2005. Data are presented as variations from the mean decadal frequency of debris flows of the last 300 yrs (1706–2005), corresponding to the mean age of trees sampled. SD (= sample depth) represents the number of samples available at the beginning of each 10-yr period.

and September, with not a single event registered for June after 1962. Finally, snowfalls and frozen ground inhibit debris entrainment from the starting zone (>2,600 m a.s.l.) from October to May.

[13] 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) than present, and fewer in summer. Figure 5 illustrates the seasonal shift in the occurrence of heavy precipitation events in the Swiss Alps for current climate (1961–1990 reference period) and a greenhouse climate (2071–2100) based on the IPCC A2 greenhouse-gas emissions scenario [*Intergovernmental Panel on Climate Change*, 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. The 99% quantile corresponds to just over 60 mm day^{-1}, and the increase in the number of extreme precipitation events (over 30% between the two periods) supports earlier findings by *Frei et al.* [1998]. Paradoxically, the impacts associated with future extreme rainfall may be reduced because of the buffering effects of snowfall on rapid runoff. This is because future springs and falls will be colder than today's summers with lower freezing levels.

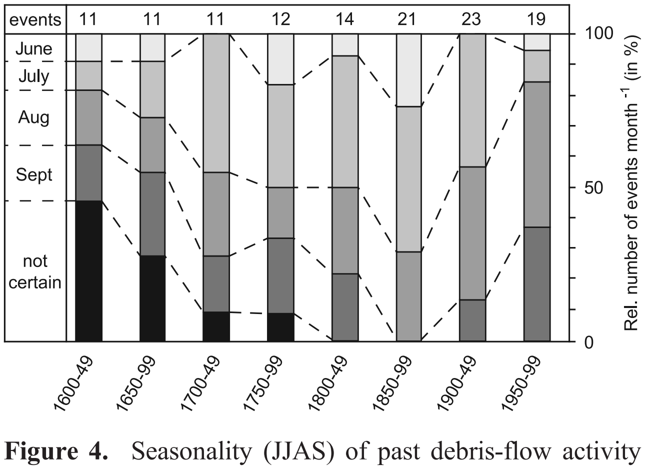

Figure 4. Seasonality (JJAS) of past debris-flow activity as inferred from the intra-annual position of rows of traumatic resin ducts (TRD) in the tree ring as well as based on archival data.

4. Discussion

[14] Results obtained from tree-ring series clearly show that the debris-flow frequency at Ritigraben increased in the 1866–1895 period that followed the maximum extent of LIA glaciers at other sites in the Alps and that events occurred most often in the early decades of the 20th century. Thereafter, debris flows were less frequently triggered in the case-study area. As a result and in contrast to studies from northern Europe [*Matthews et al.*, 1997], there does not appear to have been enhanced debris-flow activity during the LIA.

[15] The tree-ring data also indicate that relatively few debris flows occurred during the period from 1570 to 1860. As sediment availability does not seem to represent a limiting factor at Ritigraben, we infer from *Pfister's* [1999] proxy climate data that the scarcity of events was due to cooler summers and more frequent summer snowfalls in the debris-flow starting zone. The warming trend after the last LIA glacier advance in conjunction with abundant precipitation in summers and falls between 1864 and 1895 did, in contrast, favor an increase in the frequency. Similarly, the enhanced debris-flow activity reconstructed be-

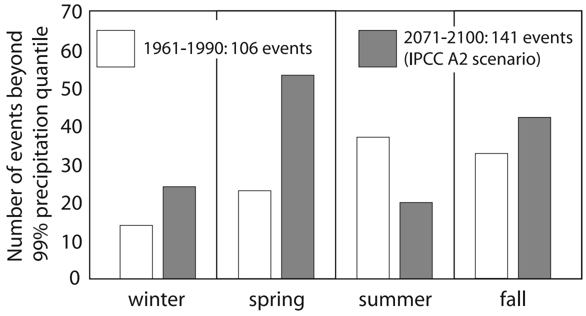

Figure 5. Number of heavy precipitation events beyond the 99% quantile in the Swiss Alps under current (1961–1990) and in a greenhouse climate (2071–2100) based on the IPCC A2 Scenario.

tween 1916 and 1935 reflects the warm-wet conditions prevailing in the Swiss Alps during that particular period of the last century.

[16] Based on observations of flooding in adjacent rivers, it also appears that debris flows at the case-study site would have been triggered more frequently by spatially limited summer thunderstorms from the 1860s until the 1980s. Since 1987, events have been released by synoptic weather systems located south of the Alps in late summer and fall. The reconstructed shift of debris-flow activity from June and July to August and September can be further 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 and Frei*, 2005].

[17] While debris flows of the past have occurred mostly during summers with greater total precipitation than average, it is conceivable that in a greenhouse climate the frequency of such events could decrease because of shifts in the occurrence of extreme precipitation from summer to spring or fall by 2100, as suggested by a number of RCMs. The impacts of future precipitation events may be lower than today, because spring and fall temperatures are suggested to remain 4–7°C degrees below current summer temperatures in a greenhouse climate [*Beniston*, 2006]; the lower freezing levels that are expected in future springs and falls compared to current summers, and the buffering effects of snow might probably reduce the risk of debris flows to be released from the starting zone. However, there could be a risk of enhanced runoff in spring if abundant rain falls upon the snow pack. Given that sediment remains readily available in the upper basin and that the channel is regularly recharged with debris, the magnitude and impacts of future summertime debris flows could be greater than currently because of warmer temperatures and higher precipitation intensities, even if the frequency of summer events is likely to decrease.

5. Conclusion

[18] Tree-ring based reconstructions of 123 debris-flow incidence in a case-study area of the Swiss Alps since AD 1570 clearly show enhanced occurrence of events during the wetter period 1864–1895 and in the early decades of the 20th century. There is, in contrast, no discernible increase of events from the 16th through mid-19th century, when debris-flow activity remained rather scarce in the investigated catchment area.

[19] From the reconstructed data and based on RCM simulations, there are also indications that, in a future greenhouse climate, debris-flow frequencies might even decrease in this torrent, 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. In contrast, strong but exceptionally extreme precipitation events in summer might trigger larger-magnitude events than they do today.

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