CLIMATIC CHANGE AND DEBRIS FLOWS IN HIGH MOUNTAIN REGIONS: THE CASE STUDY OF THE RITIGRABEN TORRENT (SWISS ALPS)

MARTINE REBETEZ
Swiss Federal Institute for Forest, Snow, and Landscape Research, Lausanne, Switzerland

RALPH LUGON and PIERRE-ALAIN BAERISWYL
Department of Geography of the University of Fribourg, Switzerland

Abstract. Debris flows in the region of Ritigraben (Valais, Swiss Alps), which generally occur in the months of August and September, have been analyzed in relation to meteorological and climatic factors. The principal trigger mechanisms for such debris flows are abundant rain on the one hand, and snow-melt and runoff on the other hand, or a combination of both. Debris flows linked to rain are likely to be triggered when total rainfall amount over a three-day period exceeds four standard deviations, i.e., a significant extreme precipitation event.

An analysis of climatological data for the last three decades in the region of Ritigraben has highlighted the fact that the number of extreme rainfall events capable of triggering debris flows in August and September has increased. Similar trends are observed for the 20th Century in all regions of Switzerland.

The general rise in temperature in a region of permafrost may also play a role in the response of slope stability to extreme precipitation. At the foot of the Ritigraben, warming trends of both minimum and maximum temperatures have been particularly marked in the last two decades.

1. Introduction

The latitude and altitude of different mountain systems determine the relative amount of snow and ice at high elevations and intense rainfall at lower elevations. Because of the amount of precipitation and the nature of the orography, and the fact that many of these mountains are located in seismically-active regions, the added effect of intense rainfall in low to middle altitude regions is to produce some of the highest global rates of slope erosion (Beniston et al., 1995). Climate change could alter the magnitude and/or frequency of a wide range of geomorphologic processes (Eybergen and Imeson, 1989). In particular, higher precipitation, especially during extreme events, can augment the risk of erosion. Precipitation is not only a source of water in mountain terrain, it is also one of the trigger factors for debris flows, landslides and slope failure. However, potential for increased erosion in a particular region depends on a number of other factors, related to topography, geology, soil types and farming and conservation practices.

In the Swiss Alps, recent studies have highlighted a strong warming signal (Beniston et al., 1994), particularly during the winter season and for minimum temperatures; the warming trends are of greater amplitude than the global warming tendencies observed in recent decades (Jones and Wigley, 1990; Houghton et

Climatic Change **36:** 371–389, 1997.

al., 1990, 1992; IPCC, 1996). Such trends have also been reported for other parts of the Alps (Auer and Böhm, 1994; Breiling and Charamza, 1994). Furthermore, there appears to be a significant altitudinal dependency of minimum temperature trends with height, i.e., the temperature anomalies increase with height, so that warming appears to be more important at high elevations than at lower elevations (Beniston and Rebetez, 1996). This could favor certain slope instability processes, in particular those linked to material cohesion by permafrost. Indeed, Zimmermann (1990a,b), Zimmermann and Haeberli (1992), Haeberli (1990, 1994), Haeberli et al. (1990, 1993) demonstrated that climatic warming during the 19th and 20th centuries had indirect effects on the formation of debris flows in the Swiss Alps. As a consequence of glacier retreat since 1850, and probably also of the degradation of permafrost, large quantities of loose material are now exposed to weathering. Relatively few studies have investigated the response of permafrost in high mountain regions to 20th Century warming. Haeberli et al. (1993, p. 170) consider that permafrost reactions to atmospheric warming generally take place in the form of:

(1) active layer thickening with thaw settlement in supersaturated materials (immediate response; time scale in years);
(2) disturbance of temperature distribution at depth (heat flow reduction; intermediate response; time scale in years to decades);
(3) basal melting of permafrost with thaw settlement in supersaturated materials (final response with a delay of several decades; lasting decades, centuries or even millenia).

However, precipitation, which has a direct and mainly short term influence on the triggering of debris flows, exhibits very high variability, and few trends which are statistically significant in the Swiss and Austrian Alps (Beniston et al., 1994; Auer and Böhm, 1994). This is not the case everywhere, as demonstrated by the decreasing trend found in the Croatian prealpine region for the period 1891–1990 (Gajic-Capka, 1993). Warmer summers tend to be associated with less precipitation and colder summers with more precipitation, mainly in terms of the frequency of occurrence of precipitation, but also in terms of its abundance (Rebetez, 1996b). However, the triggering of debris flows is not linked to average precipitation but to extreme events (Caine, 1980; Innes, 1983, 1985). These are difficult to define and there are no discernible trends in the 20th Century other than that reported by Dessens (1995) which shows a significant correlation between minimum temperatures and the severity of hailstorm events in France.

The topic of local and regional prediction methods for the triggering of landslides has been reviewed by Sidle et al. (1985) and by Crozier (1986). Their overview suggests that it is possible to define a critical threshold beyond which a debris flow or a landslide may be triggered; this can enable probability forecasting of the activity of slope movements. What is generally sought in such an approach is a climatic triggering threshold, based on rainfall intensity combined with conditions preceding the event (wet or dry). For example, Caine's (1980) threshold for debris flows and the initiation of shallow landslides is a combination of medium rainfall intensity and rainfall duration. Using the concept of climatic thresholds, Keefer et al. (1987) have been able to set up a real-time alarm system aimed at issuing warnings of debris flows for the San Fransisco Bay region of California. However, such predictions of debris flow occurences are possible only with a dense network of rain gauges, as well as a sound knowledge of the geology and hydrology of a given area.

One objective of this paper is to underline the links which exist between the triggering of debris flows and regional climatic and meteorological conditions, based on statistics of surface observations; a second aim is to determine whether conditions favorable for the triggering of debris flows are currently increasing or decreasing in the Alps. The sedimentary caracteristics of the Ritigraben torrent system (Valais Alps, Switzerland) are briefly presented and discussed.

2. Terminology

Debris flows may be defined in very broad terms as rapid mass movement of granular solids, water and air (Varnes, 1978). In this article, the term refers to 'a mass movement that involves water-charged, predominantly coarse-grained inorganic and organic material flowing rapidly down a steep, confined, pre-existing channel' (Rickenmann, 1990). Debris flows are able to travel over long distances and may transport large amounts of debris within a short time span (Zimmermann and Haeberli, 1992). Their typical depositional forms include (Zimmermann, 1990a; Costa, 1988) construction of levees on both sides of the flow path and deposition of non-sorted material with a uniform distribution of sizes ranging from clay to boulders on the alluvial fan.

The common conditions for debris flow activity are steep slopes, loose materials and wet conditions (Lewin and Warburton, 1994). According to Zimmermann and Haeberli (1992), the triggering of a debris flow has both direct and indirect causes. Sedimentary properties, i.e., the characteristics of loose materials and their potential instability on steep slopes, are indirect causes. The direct cause is a particular hydrometeorologic event, such as a thunderstorm, often in combination with periods of rapid snowmelt, or prolonged rainfall. Debris flows are sometimes also triggered by a sudden release of water stored under a glacier or by the breaching of an ice or morainic dam (Haeberli, 1992a; Evans and Clague, 1994; Walder and Driedger, 1994).

In the alpine and prealpine areas of Switzerland, debris flows are widespread geomorphologic phenomena (Zimmermann, 1990b) whose activity can severely impact upon mountain communities. In the Swiss Alps, many villages, tourist resorts and their infrastructure, roads and railways, are built in the immediate vicinity of debris flow paths and on the related alluvial fans. Alpine populations have always been aware of the threat to their villages which such catastrophic geomorphologic processes represent; ancient legends bear witness to this ancestral knowledge (Neininger and Haeberli, 1992). A certain level of risk related to geomorphic catastrophes have always been accepted, in addition to climate related risks to crops, such as late frost and excessive precipitation during the growth period (Pfister, 1988; Rebetez and Barras, 1993; Rebetez, 1994). As a consequence of the important development of tourism in these mountain areas during the 20th century, climatic modifications may have different repercussions today and in the future than they had in the past (Abegg and Froesch, 1994; Breiling and Charamza, 1994; Rebetez, 1996a). With the extension of mountain resorts and infrastructure (ski lifts, ski runs, access roads, etc.), the socio-economic consequences of debris flows need to be emphasised, as they are likely to be more important than in the past.

3. Parameters and Sites

The catchment area of the Ritigraben is situated in the Pennine Alps (Canton of Valais), in south-western Switzerland, on the slope of a large intra-alpine valley, the Mattertal. Debris flows in the Ritigraben directly threaten several roads and bridges, a railway line as well as two villages built in the close vicinity of the Ritigraben, namely Grächen and Sankt Niklaus.

The torrent system of the Ritigraben (Figure 1a) is oriented west/north west and spans a vertical range of approximately 2000 m, from 1050 m (valley floor) up to 3100 m (altitude of the upper ridge). The upper part of this torrent system is situated in the alpine periglacial zone, characterized by the presence of discontinuous frozen ground (King and Akerman, 1993). A rock glacier (see for example Barsch 1992; Haeberli 1985; Martin and Whalley, 1987, for definitions), estimated to be several tens of meters thick occupies a large part of the headwater basin. The existence of permafrost within the whole of this superficial formation is confirmed by indirect observations using the BTS method (Bottom Temperature of the winter Snow cover) (Gardaz et al., 1995; see Haeberli, 1973; and Hoelzle, 1994, for description of the method), by geoelectrical soundings (Lugon, 1997; see Vonder Mühll, 1993, for description of the method applied to mountain permafrost) and by direct observations of ice in the ground at 2550 m at the front of the rock glacier. The latter is in an unstable position at the location of the Ritigraben springs (Figure 1b). About ten years ago the construction of a ski run modified the natural morphology of the surface of the rock glacier in places. A backfill of finer material replaced the original metric blocks to allow the passage of skiers. The long-term consequences of this artificial modification on the permafrost are not known (see also Haeberli, 1992b).

The Ritigraben torrent is 3.5 km long from the front of the rock glacier (2550 m) to its confluence with the Mattervispa (1050 m), and its slope varies between 15° and 35° (according to data in Mani, 1994). At this point, the catchment area is 1.4 km^2

Figure 1a. Torrent system of the Ritigraben with (1) rock glacier, (2) present flow path of debris flows and (3) alluvial fan; frame shows the area enlarged in Figure 1b). Early snow covers part of the alpine periglacial zone (photo taken in October 1995).

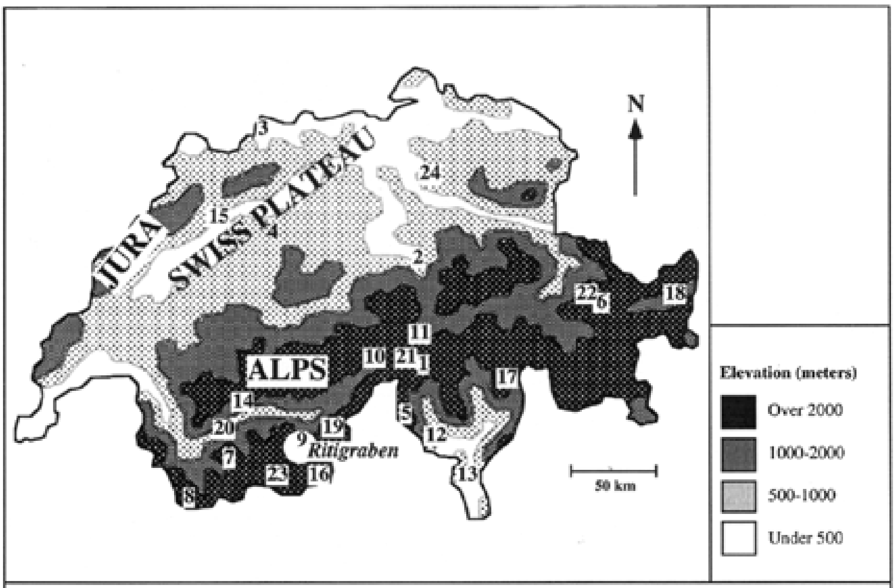
(Service hydrologique et géologique national, 1994). An intermediate alluvial fan has formed on a structural terrace. However, at the confluence with the Mattervispa, there is no alluvial fan and material transported by debris flows directly reaches the main river.

The Ritigraben area is subject to important slope instability phenomena. A large deep-seated slump affects part of the slope (constituted mainly of gneiss) on

Figure 1b. Starting zone of the debris flow of September 24, 1993, at the front of the rock glacier. Following this catastrophic event, massive ground ice (marked with arrows) was exposed at the surface within scars. One year later, this photo shows that the permafrost ice has not yet completely melted. An asterisk indicates the location of a spring of the Ritigraben torrent. Note the ski run in the back (photo taken on September 7, 1994).

which the torrent system of the Ritigraben evolves (Bearth, 1980). This is visible through the chaotic nature of the rock outcrops. The instability of the rock outcrops, enhanced by seismic hazards in this area of Switzerland (Mayer–Rosa, 1986), is the source of considerable sedimentary deposits in the torrent system. The presence of the rock glacier, whose front is in an unstable position at the Ritigraben spring probably plays a role in the dynamics of the Ritigraben debris flows.

Climatic data were used from meteorological stations indicated in Figure 2; all climatic data originates from the Swiss Climate Data Base (SCDB) (Bantle, 1989). Grächen is the closest climatological station to the study area, but its data are only available from 1966 onwards. Precipitation measured there shows that the area is remarkably dry. Indeed, measurements taken there since the start of the Century were for a long time considered to be susceptible to error (Uttinger, 1949; Bouët, 1950); they were only digitized in the SCDB for the period beginning in 1966. At Grächen the average annual rainfall for the period 1966–1994 is 630 mm, i.e., a value similar to that measured at the bottom of the Rhone valley in Central- and Upper-Valais, a rain-shadow area and one of the driest in Switzerland (620 mm in Sion during the same period). Only Lower-Engadine has comparable values (730 mm in Scuol for the same period). In comparison, for the same period,



1	Airolo (1149 m, 1931-80)	14	Montana (1495 m, 1931-94)
2	Altdorf (451m, 1901-1994)	15	Neuchâtel (487 m, 1901-94)
3	Basel (317m, 1901-1994)	16	Saas Almagell (1680 m, 1971-94)
4	Bern (570m, 1901-1994)	17	San Bernardino (1628 m, 1971-94)
5	Bosco Gurin (1505 m, 1964-94)	18	Scuol (1295 m, 1931-94)
6	Davos (1590 m, 1901-94)	19	Simplon Dorf (1495 m, 1971-94)
7	Gde Dixence (2166 m, 1965-85)	20	Sion (542 m, 1901-1977) Sion-a (483 m, 1978-1994)
8	Gd-St-Bernard (2479 m, 1934-94)	21	St-Gotthard (2090 m, 1903-1970)
9	**Grächen (1617 m, 1966-94)**	22	Weissfluhjoch (2540 m, 1959-94)
10	Grimsel (1950 m, 1964-94)	23	Zermatt (1638 m, 1960-71, 1982-94)
11	Gütsch (2288m, 1971-94)	24	Zürich (569 m, 1901-94)
12	Locarno-Monti (379 m, 1935-94)		
13	Lugano (276 m, 1901-94)		

Figure 2. Map of Switzerland showing the location of the climatological stations and of the Ritigraben.

2240 mm were registered at the Grand-St-Bernard, and 1950 mm at Bosco-Gurin. Both are just over 50 km away from Grächen, but have different exposure with respect to the impact of frontal systems, in particular those originating South of the Alps. At a similar elevation, Bosco-Gurin therefore has three times more precipitation than Grächen. In Simplon-Dorf, 20 km away from Grächen, the values are twice as high (1310 mm for the period 1971–1994).

4. Catastrophic Events

An inventory of floods was established by Pfister and Haechler (1990) for Valais and elsewhere in Switzerland between the years 1922 and 1986. Röthlisberger (1991) conducted a similar study for the whole of Switzerland between 1963 and 1988. Mani (1994) indentified the most important debris flows in the Ritigraben during the 20th century. Schnydrig (1952), also recorded several large debris flows produced by the Ritigraben.

The Ritigraben produced 9 large debris flows between 1921 (Schnydrig, 1952) or 1922 (Mani, 1994) and today (see Table I); the frequency of occurrence of these debris flows has increased since the late 1980s, with four major events between 1987 and 1994. Without providing precise dates, Schnydig (1952) mentions two other large debris flows which seem to have occurred in autumn prior to 1921. The event of September 24, 1993, was particularly catastrophic for local infrastucture since the debris flow cut across two roads, a railway line and removed a bridge. The material transported created a natural dam on the Mattervispa, outlet of the Ritigraben; this obstruction flooded the St. Niklaus filtering plant and 20 hectares of farmland were covered with debris (Service Hydrologique et Géologique National, 1994). The volume of material deposited in the Mattervispa was estimated at 60,000–90,000 m^3 by Mani (1994), which, according to the scale classification suggested by Innes (1983), may be considered to be a medium-scale debris flow (1,000–100,000 m$^{3)}$.

All debris flows, other than the 1962 event, occurred at the end of summer and/or beginning of autumn, at a time of year when the active layer of permafrost is unfrozen in the periglacial belt. Meteorological conditions favoring the triggering of debris flows are generally those which advect large quantities of rain to the Alps. Seven debris flows were triggered in this manner. In two other cases (1962 and 1994) snowmelt was the triggering factor.

In three cases (1921/22, 1953 and 1993), it was shown that the zone where the flow started was situated above 2400 m (Mani, 1994), i.e., in the alpine periglacial and within the zone of discontinuous permafrost in the Swiss Alps (Haeberli, 1990). At the time of the 1993 event, which is the best documented to date, the starting zone was situated at the front of the rock glacier.

5. Statistical Determination of Meteorological Events in Relation to the Triggering of Debris Flows

Contrary to research undertaken until now (Caine, 1980; Innes, 1983; Crozier, 1986), the critical threshold of precipitation above which a debris flow is triggered in the Ritigraben was determined by choosing a statistical parameter valid for all measurement sites, whatever the average values usually attained in each particular case, i.e., a relative value instead of an absolute threshold. This was done in order to be able to apply the results of this study to the search of trends in extreme precipitation events in other precipitation series, particularly at other meteorological stations in Switzerland, where data are available from the beginning of the 20th century (see Section 6 hereafter). Standard deviation was chosen, as it constitutes a statistical parameter which allows the determination of relative extreme values.

Table I

Record of known large debris flows during the 20th century in the Ritigraben area

Year	Days
1921/22	Precise date unknown. 1921 according to Schnydrig (1952), 1922 according to Mani (1994)
1948	4 September
1953	23–24 September
1962	End of June
1977	29–30 August
1987	24–25 August
1991	8–9 August
1993	24 September
1994	24 September

Source: Mani (1994) and Schnydrig (1952).

An analysis of precipitation data in August and September with data since 1966 (which is the observation period available at Grächen, within the study area) has been carried on in order to determine a threshold best linked with the triggering of debris flows. This threshold had to be defined as a standard deviation level and a duration, i.e., the time for which the precipitation sum is taken into account. Precipitation sums for one day and for series of between two and five days (all intervals in the record, including overlapping ones) have been compared with data concerning debris flows at Ritigraben.

The results of this analysis have shown that the coincidence between triggering of debris flows and extreme precipitation events (whatever the length of the period taken into consideration, i.e., one to six days) was always best for the meteorological station of Grächen, compared to the other climatological stations. Considering only the Grächen data, results showed that the coincidence with the triggering of debris flows was highest for the 4σ threshold with a period of three days taken into consideration. Figure 3 illustrates the values corresponding to all August and September three-day intervals in the record and shows in particular the levels reached by the extreme events exceeding the 4σ threshold. Note that 1% of cases exceeded this threshold. (Other good relationships existed for a period of four days with a threshold of 3.5σ, and for a period of five days with a threshold of 3σ; the best relationship, however, was found for the $4\sigma/3$ day period). Figure 3 shows how the levels reached by the precipitation sums in September 1993 were exceptional, even compared to the other extreme events.

The dates appearing for Grächen for three-day intervals with precipitation higher than the threshold fixed at 4σ are presented in Table II. The occurences or non-occurences of debris flows during these extreme precipitation events are listed in the

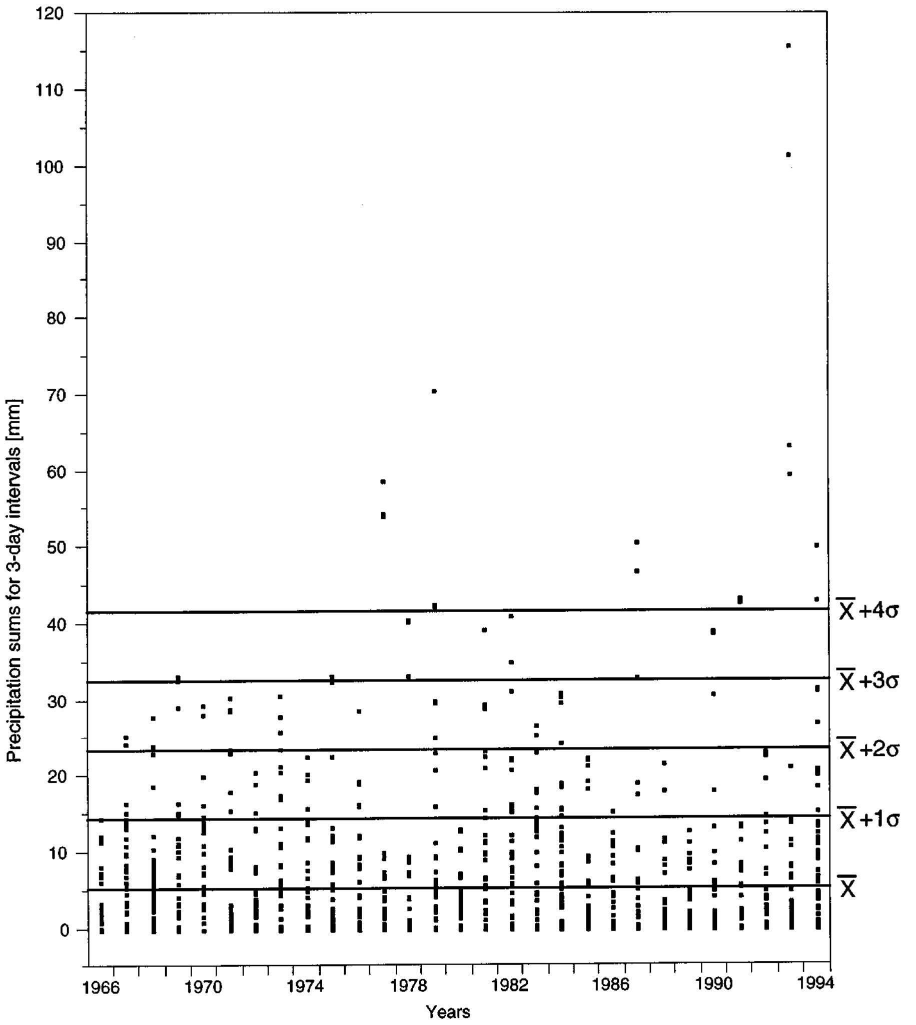


Figure 3. Precipitation sums for all August and September three-day intervals in the Grächen record between 1966 and 1994.

last column. One single debris flow event was not linked to exceptional precipitation event, namely that of September 1994; here the melting of large quantities of early snow played an important role, whereas rainfall was only of secondary importance (14 mm in three days at Grächen, from September 22 to September 24, 1994).

In 1979, very high rainfall was recorded between August 16 and August 18, without triggering of debris flows in the Ritigraben. This case is exceptional, especially as only 1993 precipitation was higher. In the other cases, lesser precipitation was sufficient to trigger debris flows. Analysis of meteorological conditions shows that they were not fundamentally different in 1979 to what they were in years when debris flows were triggered. The determining factor in this particular case seems to

Table II

Dates at which precipitation exceeded 4σ for the sum of 3 consecutive days in Grächen, between 1966 and 1994, in August and September

Dates of periods with a sum of precipitation $> +4\sigma$	Day of maximum precipitation	Sum of precipitation during the 3 days	Dates of debris flows
27–29 August 1977	29 August 1977	54.3 mm	29–30 August 1977
28–30 August 1977	29 August 1977	58.6 mm	29–30 August 1977
29–31 August 1977	29 August 1977	53.7 mm	29–30 August 1977
16–18 August 1979	18 August 1979	70.5 mm	None
17–19 August 1979	18 August 1979	42.4 mm	None
18–20 August 1979	18 August 1979	42.2 mm	None
22–24 August 1987	24 August 1987	46.9 mm	24–25 August 1987
23–25 August 1987	24 August 1987	50.7 mm	24–25 August 1987
6–8 August 1991	8 August 1991	43.3 mm	8–9 August 1991
7–9 August 1991	8 August 1991	43.3 mm	8–9 August 1991
8–10 August 1991	8 August 1991	43.1 mm	8–9 August 1991
21–23 September 1993	23 Sept. 1993	59.4 mm	24 September 1993
22–24 September 1993	24 Sept. 1993	115.8 mm	24 September 1993
23–25 September 1993	24 Sept. 1993	101.4 mm	24 September 1993
24–26 September 1993	24 Sept. 1993	63.1 mm	24 September 1993
5–7 August 1994	6 August 1994	43 mm	None
6–8 August 1994	6 August 1994	50 mm	None

be the lack of sufficient sediments for a debris flow to occur, i.e., these may have been removed from the torrent system by the previous flow in 1977. This event underlines the importance of the availability of sediments as an essential factor in the triggering of debris flows. However, debris flows occurred successively in 1991, 1993 and 1994 at one and two year intervals only, implying that in these cases, sediments were once again available two years and one year after debris flows, respectively. In August 1994, precipitation just exceeded the 4σ limit at the beginning of the month, but the debris flow was not triggered until snowmelt occurred at the end of September. Following the catastrophic 1993 debris flow, permafrost ice appeared at the surface within scars situated at the front of the rock glacier (Figure 1b). During the summer of 1994, regular visits to the study area revealed intense regressive erosion inside these scars due to the degradation of permafrost exposed to the open air (a retreat of about 1 meter was observed in some places), thus providing an important source of unconsolidated material in the Ritigraben. At the beginning of August, precipitation contributed to increasing the sediment load, without however being sufficiently important to generate a debris flow; this was finally triggered by snowmelt.

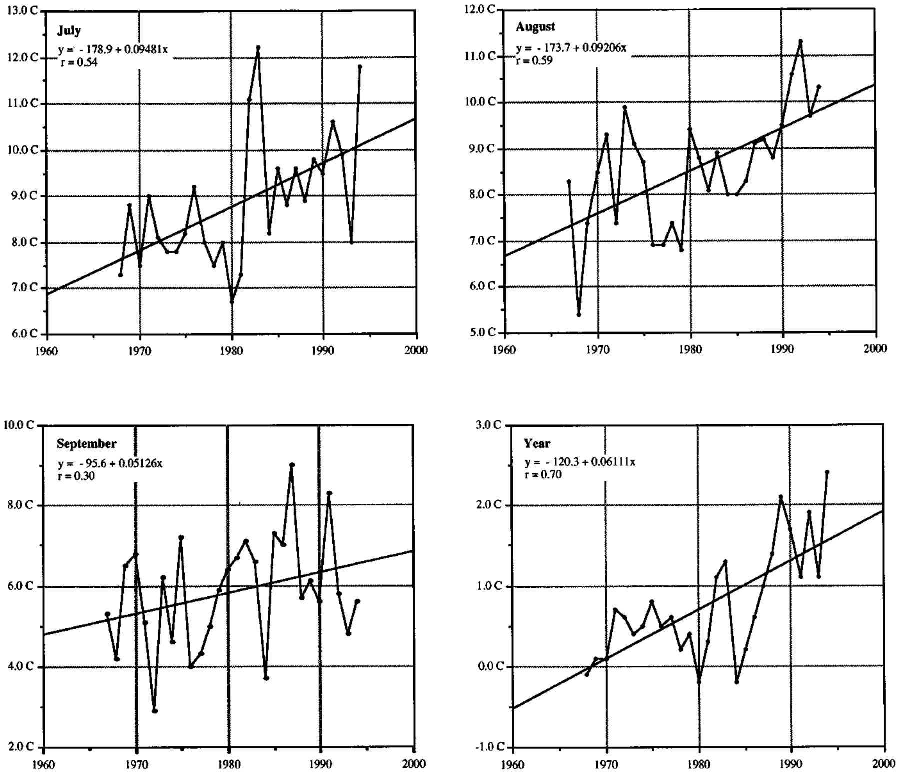


Figure 4a. Evolution of minimum temperatures at Grächen between 1966 and 1994: monthly averages in July, August and September, and yearly averages.

The instability of the Ritigraben torrent system could in part be related to temperature rise since the middle of the last century, and in particular since 1980. Higher temperatures play a key role in the availability of sediments through glacier retreat and its impact on permafrost (Haeberli et al., 1993; Haeberli, 1994). Temperatures, particularly minimum temperatures, are known to have risen in the Swiss Alps during the 20th century (Beniston et al., 1994; Haeberli, 1990). It is also known that the rise of minimum temperatures in the Alps is more marked at higher elevations than in the valleys (Beniston and Rebetez, 1996). Figure 4 shows that warming is particularly pronounced at Grächen, not only for annual averages but also specifically in July and August, and to a lesser degree in September. This warming has been particularly important since 1980, the period which has experienced the highest global temperature increases this century (Jones and Wigley, 1990; Houghton et al., 1990, 1992; IPCC, 1996). There is a possibility, which is difficult to verify, that the presence of a ski run and the modification of the natural arrangement of the surface of the rock glacier (a backfill of finer material having replaced the original blocks) may have influenced the availability of sediments.

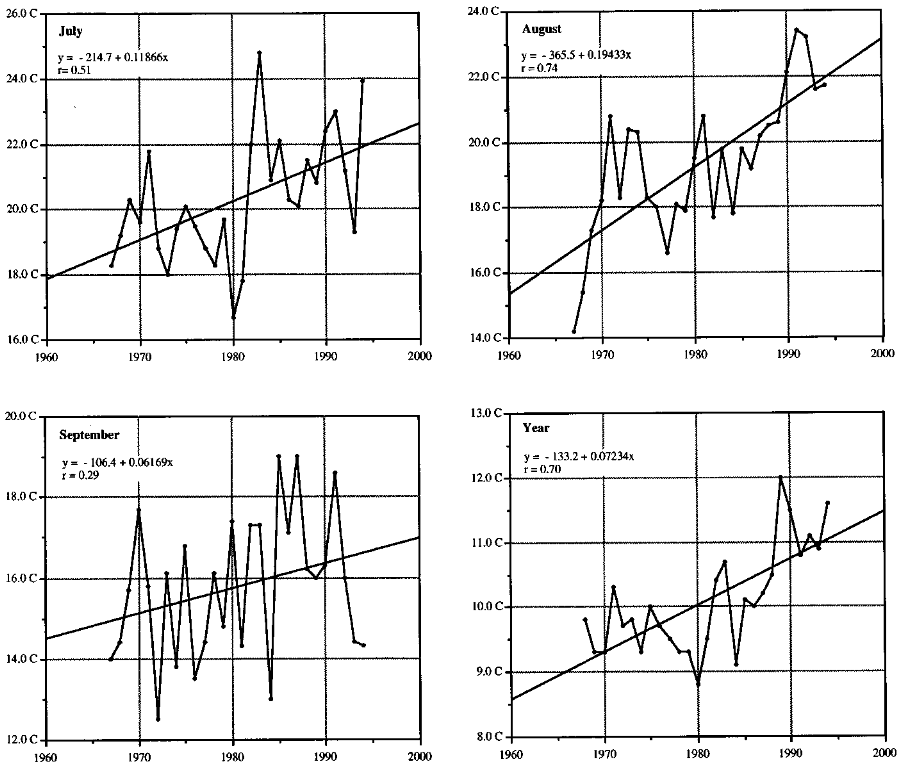


Figure 4b. Evolution of maximum temperatures at Grächen between 1966 and 1994: monthly averages in July, August and September, and yearly averages.

6. Long Term Trends in the Frequency of Occurrence of Extreme Precipitation Events

In addition to the availability of sediments and the impact of global temperature modifications is the question of whether there is an increasing frequency of extreme precipitation events capable of triggering debris flows. Indeed, although it is difficult to define a trend in mean precipitation due to the high variability of the parameter (Beniston et al., 1994; Auer and Boehm, 1994) and although the overall tendency appears to be towards a general decrease of mean precipitation in summer (Gajic-Capka, 1993; Rebetez, 1996b), the situation may be different in the case of extreme precipitation. For example, in the prealpine region of Croatia (Zagreb-Gric observatory), the precipitation maxima for the very short time intervals (10–30 min) and the longer ones (8–24 h) do not exhibit any trend, but for intervals of 40 min to 4 h an increase has been highlighted in recent years (Gajic-Capka, 1990). Dessens (1995) has shown that there is a statistically significant positive correlation between severe storms and minimum temperature.

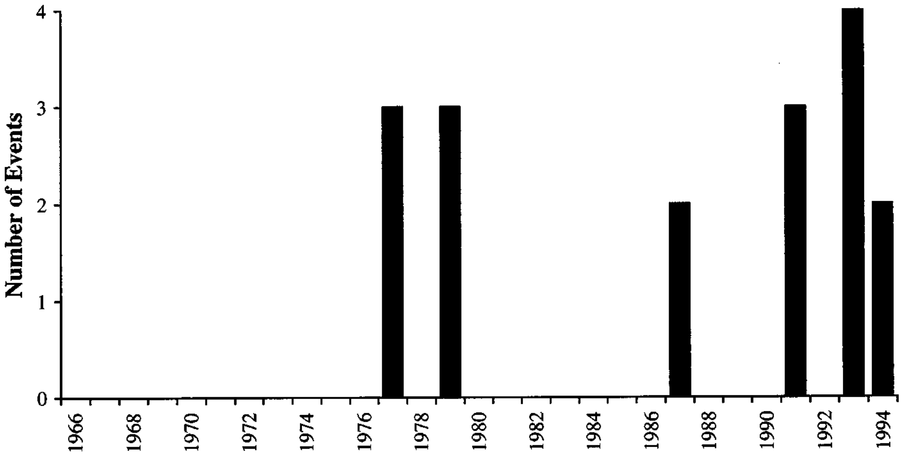


Figure 5. Extreme precipitation events (sum of precipitation of 3 consecutive days $> 4\sigma$) at Grächen, between 1966 and 1994: absolute number of cases per year.

We have analysed our data to look for trends in the series of extreme precipitation events in the sense defined in section 5. Over the time span for which data is available at Grächen, i.e., between 1966 and 1994, the frequency of rainfall periods liable to trigger debris flows is on the increase, as shown by Figure 5. The trend remains approximately the same if one considers that each series of three days exceeding 4σ constitutes an event, as in Figure 5, or if one considers consecutive episodes as one and the same event.

Transposing the same trend research to longer time series, we could observe that, for sites with uninterrupted data between 1901 and 1994 (Figure 6), trends were positive at Lugano (South of the Alps), Basel, Bern, Neuchâtel and Zurich and at higher elevations (Davos). Only Altdorf (451 m, at the intersection of two valleys close to the Gotthardpass and the Klausenpass) did not show any particular trend; precipitation data from Säntis cannot be suitably used because of the frequent change in the location of the rain gauge. During the period available at Grächen, trends are also positive at all stations other than Altdorf. This means that, with only one exception, extreme precipitation events capable of triggering debris flows have been on the increase during the 20th century in Switzerland. Note that the exception of Altdorf is likely due to a change in location of the rain gauge.

7. Conclusions

Analyses of cases of high rainfall in relation to debris flows in the Ritigraben area in August or in September have shown that in all situations where snowmelt did not have an influence, the necessary condition for triggering debris flows is that rainfall must exceed 4σ for the accumulated precipitation on three consecutive

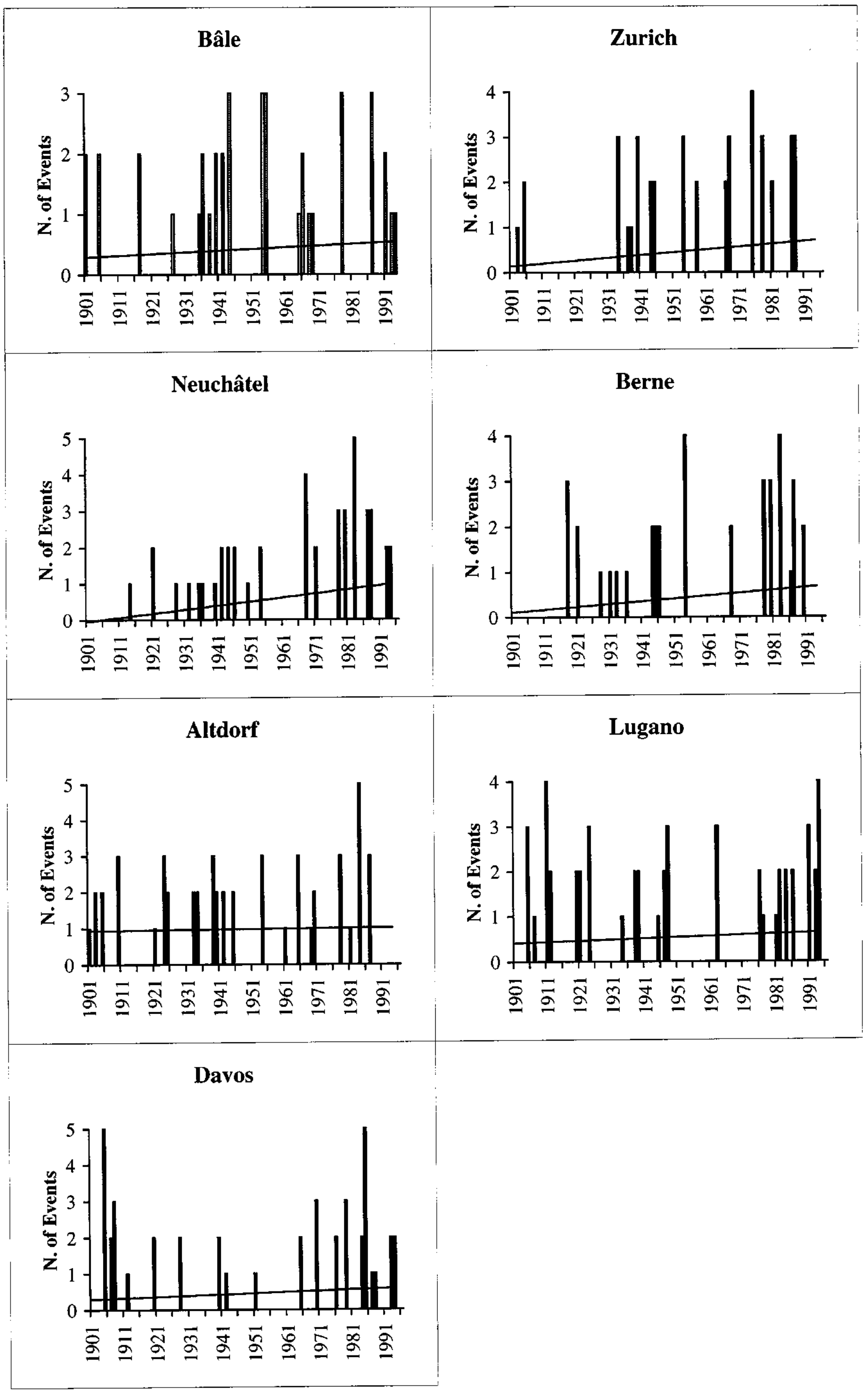


Figure 6. Extreme precipitation events (sum of precipitation of 3 consecutive days $> 4\sigma$) for 7 Swiss stations, between 1901 and 1994: absolute number of cases per year and linear trend.

days. Observations at Grächen show 1% of cases exceeding this threshold. During the period for which data is available (1966–1994), no debris flows were triggered when rainfall amount was below this threshold, or if water from snowmelt was not added to precipitation. In two cases, however, no debris flow occurred, despite the fact that the criterion for rainfall was fulfilled. It is essential that there be a sufficient amount of sedimentary material available to feed the debris flow. In 1979, material had been removed by a debris flow two years earlier. In the August 1994 rainfall event, material had been removed the previous autumn, but a debris flow was subsequently triggered in September 1994 by a combination of precipitation and snowmelt.

The frequency of extreme precipitation events is increasing at Grächen and elsewhere in Switzerland. This increase in frequency of extreme rainfall may explain the higher frequency of debris flows over the past few years in the Ritigraben. However, it is important to note that all extreme precipitation events having occurred since 1987 coincided with favorable sedimentary conditions, including consecutive years or for two events separated by only two years (1991, 1993, 1994). This availability of sedimentary material could be a completely local phenomenon linked to a morphodynamic crisis of the Ritigraben torrent system. However, this crisis could also be linked to global climate warming. In the eastern Swiss Alps, borehole observations indicate an increase of permafrost temperatures during the last decade at a rate of 0.1 K/year (Haeberli, 1995; Vonder Mühll et al., 1994). In the Swiss Alps and in Grächen in particular, temperatures have risen during the 20th century, and particularly during the last 10–15 years, with far greater amplitudes than those observed at the global level.

Acknowledgements

This research has been supported by the Swiss National Science Foundation, grant numbers 4031-38271 and 4031-39083, by the Institute of Geography of the University of Fribourg and by the Forest Investigation Programme, a joint project between the Swiss Federal Office of the Environment, Forests and Landscape (BUWAL, Bern) and the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL, Birmensdorf. We thank Wilfried Haeberli, Martin Beniston and an anonymous reviewer for their useful comments.

References

Abegg, B. and Froesch, R.: 1994, ‘Climate Change and Winter Tourism: Impact on Transport Companies in the Swiss Canton of Graubünden’, in: Beniston, M. (ed.), *Mountain Environments in Changing Climates*, Routledge Publishing Company, London and New York, pp. 328–340.

Auer, I. and Böhm, R.: 1994, ‘Combined Temperature-Precipitation Variations in Austria during the Instrumental Period’, *Theor. Appl. Climatol.* **49**, 161–174.

Bantle, H.: 1989, *Programmdokumentation Klima-Datenbank am RZ-ETH Zurich*, Swiss Meteorological Institute, Zurich.

Barsch, D.: 1992, 'Permafrost Creep and Rockglacier', *Permafrost and Periglacial Processes* **3** (3), 175–188.

Bearth, P.: 1980, *Atlas géologique de la Suisse 1/25'000, feuille 1308*, St-Niklaus, Commission géologique suisse.

Beniston, M., Rebetez, M., Giorgi, F,. and Marinucci, R.: 1994, 'An Analysis of Regional Climate Change in Switzerland', *Theor. Appl. Climatol.* **49**, 135–159.

Beniston, M. and Rebetez, M.: 1996, 'Regional Behavior of Minimum Temperatures in Switzerland for the Period 1979–1993', *Theor. Appl. Climatol.* **53**, 231–243.

Beniston, M., Fox, D. G., Adhikary, S., Andressen, R., Guisan, A., Holten, J., Maitima, J., Price, M., and Tessier, L.: 1995, *The Impacts of Climate Change on Mountain Regions*, Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Chapter 5, Cambridge University Press, Cambridge.

Bouët M.: 1950, 'La pluie en Valais', *Bulletin de la Murithienne* **67**, 1–22.

Breiling, M. and Charamza, P.: 1994, 'Sensitivity of Mountain Runoff and Hydro-Electricity to Changing Climate', in Beniston, M. (ed.), *Mountain Environments in Changing Climates*, Routledge Publishing Company, London and New York, pp. 91–107.

Caine, N.: 1980, 'The Rainfall Intensity – Duration Control of Shallow Landslides and Debris Flows', *Geografiska Annaler* **62A** (1–2), 23–27.

Costa, J. E.: 1988, 'Rheologic, Geomorphic and Sedimentologic Differentiation of Water Floods, Hyperconcentrated Flows, and Debris Flows', in Baker, V. R., Kochel, R. G., and Patton, P. C. (eds.), *Flood Geomorphology*, John Wiley and Sons, New York, pp. 113–122.

Crozier, M. J.: 1986, *Landslides: Causes, Consequences and Environment*, Croom Helm, London.

Dessens, J.: 1995, 'Severe Convective Weather in the Context of a Nighttime Global Warming', *Geophys. Res. Lett.* **22** (10), 1241–1244.

Evans, G. E. and Clague, J. J.: 1994, 'Recent Climatic Change and Catastrophic Geomorphic Processes in Mountain Environments', *Geomorphology* **10**, 107–128.

Eybergen, J. and Imeson, F.: 1989, 'Geomorphologic Processes and Climate Change', *Catena* **16**, 307–319.

Gajic-Capka, M.: 1990, 'Maximum Precipitation for Different Short-Term Intervals', *Theor. Appl. Climatol.* **41**, 33–39.

Gajic-Capka, M.: 1993, 'Fluctuations and Trends of Annual Precipitation in Different Climatic Regions of Croatia', *Theor. Appl. Climatol.* **47**, 215–221.

Gardaz, J.-M., Lugon, R., and Monbaron, M.: 1995, 'Prospection du pergélisol de montagne à l'aide de la méthode BTS (Alpes valaisannes, Suisse)', *UKPIK, Cahiers de l'Institut de Géographie de Fribourg* **10**, 93–105.

Haeberli, W.: 1973, 'Die Basis-Temperatur der winterlichen Schneedecke als möglicher Indikator für die Verbreitung von Permafrost in den Alpen', *Z. Gletscherkunde Glazialgeol.* **9** (1–2), 221–227.

Haeberli, W.: 1985, 'Creep of Mountain Permafrost: Internal Structure and Flow of Alpine Rock Glaciers', *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie*, ETH Zürich **77**, p. 142.

Haeberli, W.: 1990, 'Permafrost', in VAW (ed.), *Schnee, Eis und Wasser der Alpen in einer wärmeren Atmosphäre, Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie,* ETH Zürich **108**, pp. 71–88.

Haeberli, W.: 1992a, 'Zur Stabilität von Moränenseen in hochalpinen Gletschergebieten', *Wasser, Energie, Luft* **84** (11/12), 361–364.

Haeberli, W.: 1992b, 'Construction, Environmental Problems and Natural Hazards in Periglacial Mountain Belts', *Permafrost Periglacial Proc.* **3** (2), 111–124.

Haeberli, W.: 1994, 'Accelerated Glacier and Permafrost Changes in the Alps', in Beniston, M. (ed.), *Mountain Environments in Changing Climates*, Routledge Publishing Company, London and New York, pp. 91–107.

Haeberli, W.: 1995, 'Climate Change Impacts on Glaciers and Permafrost', in Guisan et al. (eds.), *Potential Ecological Impacts of Climate Change in the Alps and Fennoscandian Mountains*, Conserv. Jard. Bot. Genève, pp. 97–103.

Haeberli, W., Rickenmann, D., Zimmermann, M., and Rössli, U.: 1990, 'Investigation of 1987 Debris Flows in the Swiss Alps: General Concept and Geophysical Soundings', *IAHS Publication* **194**, 303–310.

Haeberli, W., Guodong, C., Gorbunov, A. P., and Harris, S. A.: 1993, 'Mountain Permafrost and Climatic Change', *Permafrost Periglacial Proc.* **4** (2), 165–174.

Hoelzle, M.: 1994, 'Permafrost und Gletscher im Oberengadin. Grundlagen und Anwendungsbeispiele für automatisierte Schätzverfahren', *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie*, ETH Zürich **132**, p. 121.

Houghton, J. T., Jenkins, G. J., and Ephraums, J. J. (eds.): 1990, 'Intergovernmental Panel on Climate Change, Climate Change, The IPCC Scientific Assessment', *World Meteorological Organization/U.N. Environment Program*, Cambridge University Press, Cambridge.

Houghton, J. T., Callander, B. A., and Varney, S. K. (eds.): 1992, 'Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment', *World Meteorological Organization/U.N. Environment Program*, Cambridge University Press, Cambridge, p. 200.

IPCC: 1996, Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell (eds.), *Climate Change 1995: The Science of Climate Change*, Cambridge University Press, Cambridge, p. 572.

Innes, J.-L.: 1983, 'Debris Flows', *Progr. Phys. Geogr.* **7**, 469–501.

Innes, J.-L.: 1985,'Magnitude-Frequency Relations of Debris Flows in Northwest Europe', *Geografiska Annaler* **67A** (1-2), 23–32.

Jones, P. D. and Wigley, T. M. L.: 1990, 'Global Warming Trends', *Sci. Amer.* **263**, 84–91.

Keefer, D. K., Wilson, R. C., Mark, R. K., Brabb, E. E., Brown, III W. M., Ellen, S. D., Harp, E. L., Wieczorek, G. F., Alger, C. S,. and Zatkin, R. S.: 1987, 'Real-Time Landslide Warning During Heavy Rainfall', *Science* **238**, 921–925.

King, L. and Akerman, J.: 1993, 'Mountain Permafrost in Europe', in *Permafrost, Proceedings of the Sixth International Conference* **2**, Beijing, pp. 1022–1027.

Lewin, J. and Warburton , J.: 1994, 'Debris Flows in an Alpine Environment', *Geography* **79** (343), 98–107.

Lugon, R.: 1997, *Influence des changements climatiques sur la stabilité des terrains meubles en zone de pergélisol dans les Alpes valaisannes. Deux études de cas: le torrent du Ritigraben (Mattertal) et la moraine du glacier du Dolent (Val Ferret)*, Rapport final PNR 31, vdf, Hochschulverlag, Zürich (in preparation).

Mani, P.: 1994, *Ritigraben (Mattertal), Grundlagen-Zusammenstellung und erste Interpretation*, Geo7 Bericht fuer das Baudepartement des Kantons Wallis, Nr. 9407.01.

Martin, H. E. and Whalley, W. B.: (1987), 'Rock Glaciers, Part 1: Rockglacier Morphology, Classification and Distribution', *Progr. Phys. Geogr.* **11** (2), 261–282.

Mayer-Rosa, D. (ed.): 1986, *Tremblements de terre. Origine, risque et aide*, commission nationale suisse pour l'Unesco, commission suisse de géophysique.

Neininger, B. and Haeberli, W.: 1992, in Gemeinde Münster (ed.), *'Münster - als der Bach kam'*, pp. 55–77.

Pfister, C.: 1988, 'Fluctuations climatiques et prix céréaliers en Europe du XVIe au XXe siècle', *Annales E.S.C.* **41/1**, 25–53.

Pfister, C. and Hächler, S.: 1990, *Hochwasserkatastrophern im schweizerischen Alpenraum seit dem 14. Jahrhundert*, Bericht Nationales Forschungsprogramm 'Analyse der Hochwasser 1987'.

Rebetez, M. and Barras, C.: 1993, *Le Climat des Romands*, Stratus, Oron-la-Ville.

Rebetez, M.: 1994, *Perception du temps et du climat: une analyse du climat de Suisse romande sur la base des dictons populaires*, Ph. D. Thesis, University of Lausanne, Stratus, Oron-la-Ville.

Rebetez, M.: 1996a, 'Public Expectation as an Element of Human Perception of Climate Change', *Clim. Change* **32**, 495–509.

Rebetez, M.: 1996b, 'Seasonal Relationship between Temperature, Precipitation and Snow Cover in a Mountainous Region', *Theor. Appl. Climatol.* **54**, 99–106.

Rickenmann, D.: 1990, 'Bedload Transport Capacity of Slurry Flows at Steep Slopes, *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie*, ETH Zürich **103**, p. 249.

Röthlisberger, G.: 1991, 'Chronik der Unwetterschäden in der Schweiz', *Berichte der Eidgenössischen Forschunganstalt für Wald, Schnee und Landschaft* **330**, p. 122.

Schnydrig, A. L.: 1952, ‘Grächen, Walliser Bergdorf an der Mischabel’, Paul Haupt, Bern, p. 104.

Service hydrologique et géologique national: 1994, *La crue de 1993 en Valais et au Tessin, mesures effectuées et premières conclusions*, Communication 19a, Berne.

Sidle, R. C., Pearce, A. J., and O’Loughlin, C. L.: 1985, ‘Hillslope Stability and Land Use’, *Amer. Geophys. Union, Water Res. Monogr.* **11**, Washington D.C., p. 140.

Uttinger, H.: 1949, ‘Les précipitations en Suisse 1901–1940’, *Guide de l’économie hydraulique et de l’électricité en Suisse* **2**, Elektrizitätwirtschaft, Zürich, p. 103.

Varnes, D. J.: 1978, ‘Slope Movement Types and Processes’, in Schuster, R. L. and Krizek, R. J. (eds.), *Landslides Analysis and Control, Transport Res. Board Spec. Rept.* **176**, Nat. Acad. Sc., Washington D. C, pp. 11–33.

Vonder Mühll, D.: 1993, ‘Geophysikalische Untersuchungen im Permafrost des Oberengadins’, *Mitteilungen der Versuchsanstalt fuer Wasserbau, Hydrologie und Glaziologie*, ETH Zürich **122**, p. 222.

Vonder Mühll, D., Hoelzle, M., and Wagner, S.: 1994, ‘Permafrost in den Alpen’, *Die Geowissenschaften* **12** (5–6), 149–153.

Walder, J. S. and Driedger, C. L.: 1994, ‘Rapid Geomorphic Change Caused by Glacial Outburst Floods and Debris Flows along Tahoma Creek, Mount Rainier, Washington, U.S.A.’, *Arctic and Alpine Res.* **26** (4), 319–327.

Zimmermann, M.: 1990a, ‘Periglaziale Murgänge’, in VAW (ed.), *Schnee, Eis und Wasser der Alpen in einer wärmeren Atmosphäre*’, *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie*, ETH Zürich **108**, pp. 89–107.

Zimmermann, M.: 1990b, ‘Debris Flows 1987 in Switzerland: Geomorphological and Meteorological Aspects’, *IAHS, Hydrol. Mountainous Regions* **2** (194), 387–393.

Zimmermann, M. and Haeberli, W.: 1992, ‘Climatic Change and Debris Flow Activity in High-Mountain Areas – A Case Study in the Swiss Alps’, Greenhouse-Impact on Cold-Climate Ecosystems and Landscapes, *Catena Suppl.* **22**, 59–72.

(Received 22 February 1996; in revised form 31 December 1996)