Destructive snow avalanches and climate change in the Swiss Alps

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Destructive snow avalanches and climate change in the Swiss Alps

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Key words: long-term trend, snow depth, defence structures, probability, weather

ABSTRACT

Snow avalanches are an important natural hazard in alpine areas. Especially settlements and traffic routes are threatened. A better understanding of the relations between avalanche occurrence and climate is necessary to deduce possible effects of climate changes on the avalanche hazard. This study investigates the relations of climatic conditions on avalanche release from 1947–1993 and extreme snowfall events from 1896–1993. The statistical evaluation of the meteorological data shows a long-term trend in temperature, but not in snow depth and extreme snowfall events. From the meteorological long-term time series at Davos (eastern Switzerland) we tried to model the corresponding avalanche activity from 1896–1946. The modelling of the avalanche activity was not successful because the extremely sparse distribution of extreme events prevented the establishment of a reliable statistical model. Looking at potential avalanche situations in terms of extreme weather situations it can be assumed that the climatic causes for severe avalanche periods have remained stable during the past 100 years and show no sign of change in the near future.
However, the construction of defence structures in avalanche starting zones, improved zoning of hazardous areas and artificial avalanche release have reduced the probability of catastrophic events.

ZUSAMMENFASSUNG

Schnee-Lawinen sind eine bedeutende Naturgefahr in alpinen Gebieten. Siedlungen und Verkehrswege sind besonders gefährdet. Ein besseres Verständnis der Zusammenhänge zwischen dem Auftreten von Lawinen und Klima ist notwendig, um mögliche Einflüsse einer Klimaänderung abschätzen zu können. Diese Arbeit untersucht die Beziehungen zwischen Lawinenereignissen und Wetterbedingungen von 1947–1993 und extreme Schneefallereignisse von 1896–1993. Die statistische Auswertung der meteorologischen Daten zeigt einen langfristigen Anstieg der Temperatur, jedoch keine Änderung bezüglich Schneehöhe und extremen Schneefallereignissen. Aufgrund der langen meteorologischen Messreihe Davos (Schweiz), versuchten wir die entsprechende Lawinenaktivität von 1896 bis 1946 zu modellieren. Die Modellierung war wenig erfolgreich, da das seltene Auftreten extremer Ereignisse ein zuverlässiges statistisches Modell verunmöglichte. Extreme Wettersituationen, welche potentiell zu Schadenlawinensituationen führen können, sind in den vergangenen knapp 100 Jahren gleich häufig geblieben und zeigen keine Anzeichen einer Änderung. Die Konstruktion von Lawinenverbauungen, verbesserte Zonenplanung und die künstliche Auslösung von Lawinen haben die Wahrscheinlichkeit katastrophaler Ereignisse reduziert.

1. Introduction

In alpine areas snow avalanches are a natural hazard of great significance. This study is based on spontaneously released avalanches causing damage to property (buildings, traffic routes, forests, etc.), excluding avalanches triggered by skiers. Destructive avalanches are usually the result of extreme weather conditions (Föhn 1990). The effects of climate changes on the avalanche activity are hardly understood, but may be of great importance for the inhabitants of alpine areas as well as for the safety of traffic routes. Avalanches are not primarily a meteorological phenomenon, but their occurrence is mainly dependent on the stability of the snow cover, which is strongly influenced by the weather situation (Föhn & Hächler 1978). No conclusive numerical model to forecast avalanches exists today and forecasts are mainly based on the personal expertise of the forecasters. The few existing statistical and numerical models are only applicable to small areas and are based on short-term data. Direct correlation of long-term, daily meteorological data to avalanche events is the only feasible method to reach a significant improvement. General circulation patterns have shown promising connections to large avalanche events (Hächler 1987). Changes in these circulation patterns may therefore serve as an indicator for a changed avalanche activity.

The beginning of the construction of avalanche defense structures goes back to the end of the last century (Coaz 1881). The systematic extension of retaining structures in avalanche starting zones has probably a significant impact on the large scale avalanche activity after 1951. During the past 45 years

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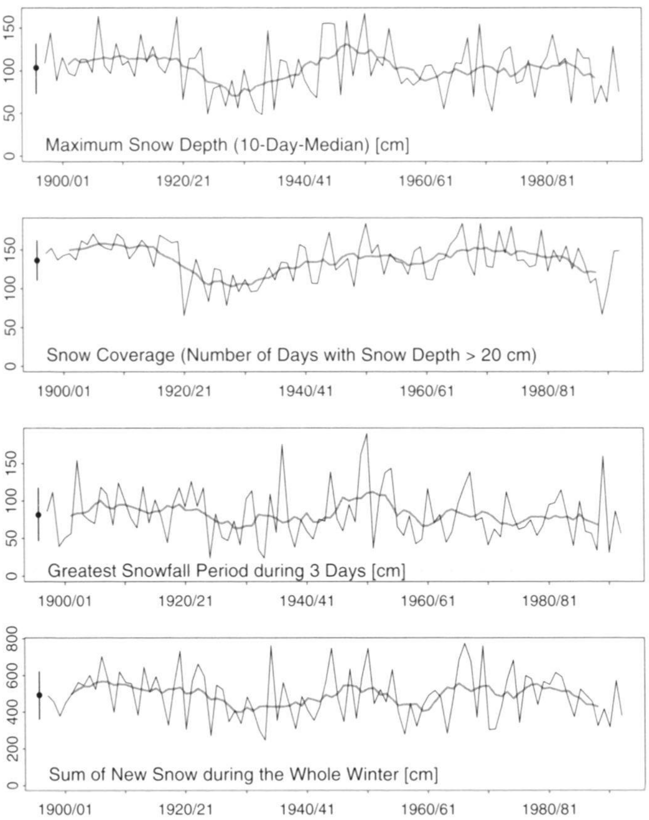

Fig. 1. Annual characteristics of the snow conditions in Davos from 1896–1993. The stippled line is the running mean over 9 years, the dot and the bar on the left indicate the mean and the standard deviation. Very low snow depths and short snow coverages occurred around 1925–1934. A recent minimum of snow coverage is in the late eighties. Due to the short period of measurements in comparison to these minima, no periodicity can be inferred.

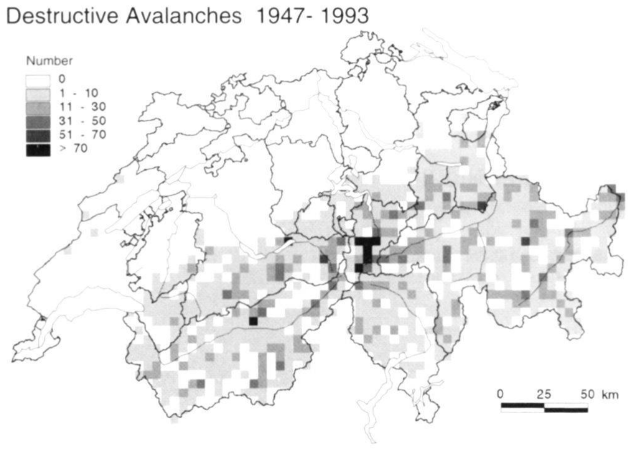

Fig. 2. Spatial distribution of destructive avalanches in Switzerland from 1947–1993. The highest concentration of destructive avalanches occurs in central Switzerland. The grid length is 5 km.

about 11 km of new snow bridges have been built every year. Artificial avalanche release with explosives has become increasingly more common und efficient, but can not be quantified due to the lack of data.

Because of the constant increase in land use (residential areas, traffic, tourism) and the simultaneously steady development of avalanche defence structures the effects of climate on the avalanche activity in the past must be deduced carefully. In this study the correlation of meteorological factors with destructive avalanches was used to find a threshold value where numerous destructive avalanches occur. Changes in the intensity and occurrence of meteorological factors could then be used to infer the potential avalanche activity.

2. Data and methods

The measurement of the general avalanche activity is difficult, because no continuous records of avalanches are available over a large area (several hundreds to thousands of km^2) and over a long period (more than 50 years). An interesting data set exists for the Davos-Weissfluhjoch area (120 km^2) with systematic avalanche records of 50 winters (de Quervain & Meister 1987). However, the land use during this time has changed considerably (development of ski fields, new residential areas) and so has the avalanche activity (artificial avalanche release, development of defence structures). Because of this situation it was necessary to look for a surrogate measure of the general avalanche activity. Only *destructive* avalanches were taken because they are the only information available in a fairly systematic manner and a comprehensive database was established (Laternser et al. 1995). Nevertheless the recordings of destructive avalanches has some disadvantages: (i) the records are not absolutely complete depending on the interest of the voluntary observers, (ii) the detailed outline of the runout zone of an avalanche is often accidental and may cause a damage or not, (iii) technical measures like artificial release, defence structures and zoning of hazardous areas change the probability of a damage.

The winter climate was primarily investigated at Davos. A 96 year continuous time series with daily data could be reconstructed with data from the Swiss Meteorological Institute and unpublished snow records from the SLF. To characterize each winters snow conditions the maximum snow depth, the duration of the snow coverage, the greatest snowfall period during 3 days and the total amount of daily new snow during the entire winter has been plotted (Fig. 1). These parameters are all related to the avalanche activity.

The snow depth shows a great short-term variability and a marked long-term fluctuation. The low values from 1925–1934 are obvious. This period is not correlated with high winter temperatures, in contrast to the low values around 1990. The snow coverage (number of days with more than 20 cm of snow) shows a similar pattern to the snow depth. The variabil-

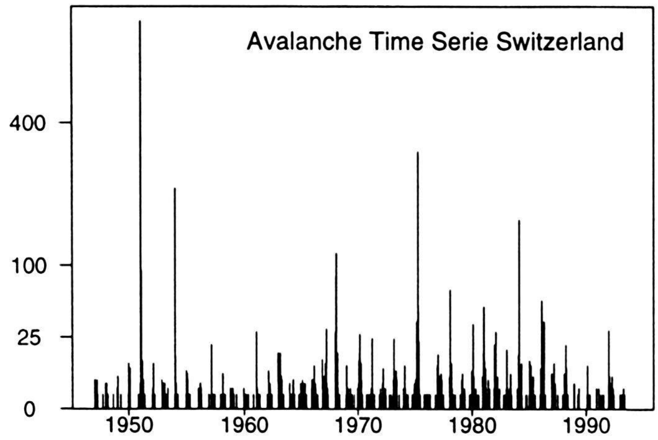

Fig. 3. Daily number of destructive avalanches in Switzerland from 1947–1993. Note the square-root transformed scale on the y-axis.

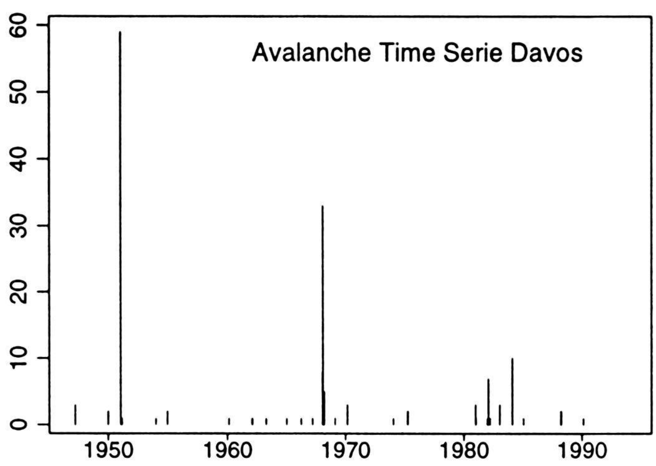

Fig. 4. Daily number of destructive avalanches in Davos from 1947–1993.

ity is rather small at the beginning of the century and increases afterwards. The greatest snowfall period during 3 days and the total amount of daily new snow during the whole winter remain stable, but show extreme variability from year to year.

The mean winter temperature in Davos was about 0.8 °C higher during the past 20 years compared to the mean from 1881–1993. Significant seasonal differences can be found. The months November–December were about 0.9 °C warmer, January–February were about 1.4 °C warmer, but with a high year to year variability, and, interestingly, March–April showed no increase in temperature.

The spatial distribution of destructive avalanches during the past 47 years is shown in Figure 2. Destructive avalanches are most concentrated in central Switzerland. Obviously high mountain ridges show few or no destructive avalanches, whereas valleys clearly stand out. A classification of the damages makes the interpretation of the damage pattern easier. Linear damages are typical along mayor traffic routes and single spots with high damage concentrations point out to endangered settlements.

The occurrence of destructive avalanches in Switzerland between 1947–1993 shows no obvious trend (Fig. 3). The great avalanche events of 1951 and 1954 are clearly visible followed by a rather long period with only small events up to 1967. Then the general level of destructive avalanches became higher again with distinct peaks in 1968, 1975 and 1984. Since the late eighties the avalanche activity is clearly reduced again up to 1996.

The situation in the surroundings of Davos shows a similar picture (Fig. 4). However, the magnitude of the large events decreases systematically. The events of 1951, 1968 and 1984 in Figure 5 show a similar spatial distribution in eastern Switzerland. But why was the 1968 event so strong and in 1984 occurred hardly any destructive avalanches in Davos? Apart from very local differences in the weather behaviour this can be explained by the fact that the defence structures around Davos have been significantly enhanced since 1969 and the restrictions to erect buildings in dangerous zones have been enforced based on the 1968 experience.

The occurrence of avalanche damages restricted to single regions shows the importance of the local weather situation. Although earlier events than 1947 are usually not well documented, no avalanche period could be found during the past 600 years which struck the entire Swiss Alps at once (Schneebeli et al. 1997).

3. Modelling

No systematic records of destructive avalanches exist before 1947. To infer the avalanche activity before this date, the avalanche activity was modelled using meteorological data. The probability of an avalanche day can be estimated using the avalanche database in respect to snow depth and the cumulative sum of new snow fallen during a succession of 3 days (Fig. 6). If both the snow depth and the 3-day new snow exceed 75 cm, the probability of a disastrous avalanche day increases significantly. Building up statistical models from these data faces several difficulties because the number of extreme events is very small. A certain class has often only one single event and a probability of one, but a nearby class has no event and consequently a probability of zero. This problem is especially severe at the edge of the empirical distribution because there are simply no values. Neither a nearest-neighbour algorithm nor a lookup table using average-shifted multidimensional histograms (Venables & Ripley 1994) have been very successful in reconstructing past avalanche events (Schneebeli et al. 1997).

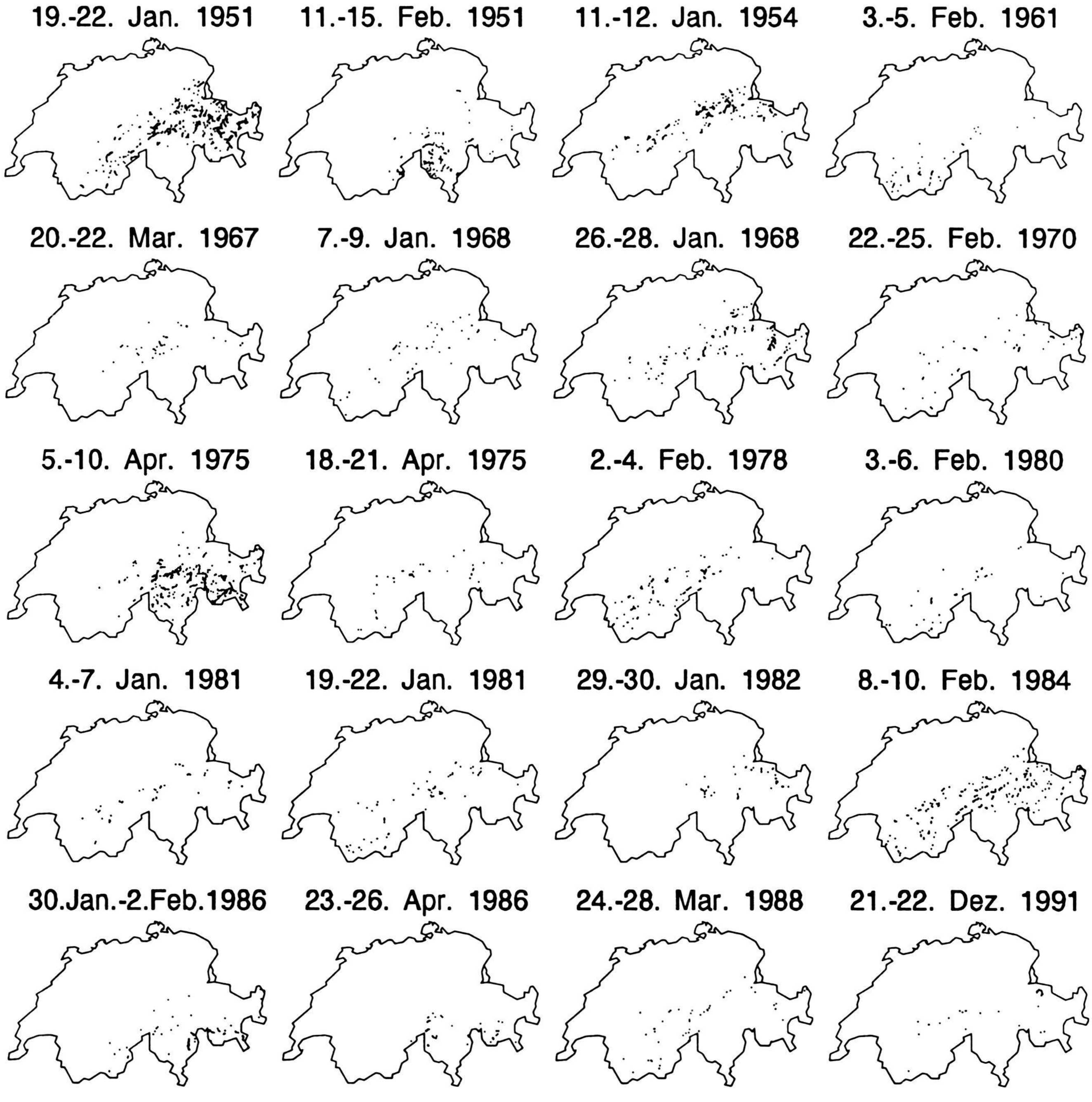

Fig. 5. Spatial distribution of the 20 largest damage situations in Switzerland from 1947–1993. Events with more than 30 destructive avalanches within 2 days have been systematically selected. Every dot shows the place of a damage.

To avoid this problem, a more direct approach was sought. The threshold value where both snow depth and 3-day new snow exceed 75 cm can be used as an indicator of the potential avalanche activity (PAA). The probability of an avalanche day is higher than 0.3 with the criterium choosen for the PAA-index (Fig. 6). A plot of the date of the event against the cumulative sum of the events shows changes in the PAA (Fig. 7). The PAA was rather constant until 1923. After this date only four events occurred until 1943. This is an exceptionally long period of low PAA. The period from 1943 to 1957 shows a reg-

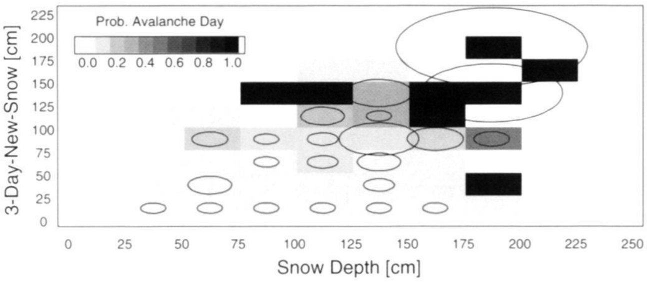

Fig. 6. Probability of an avalanche day in the Davos area considering snow depth and cumulative sum of new snow fallen during a succession of 3 days (grey levels). In addition to that the ellipses show the number of individual avalanches per avalanche day, where the largest ellipse symbolizes 58 and the smallest circle one avalanche per day. (Data period: 1947–1993, November – May.)

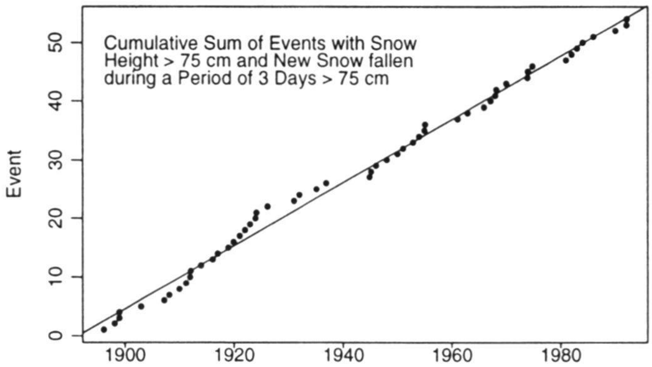

Fig. 7. Events (dots) where both the snow depth and the cumulative sum of new snow fallen during a succession of 3 days exceed 75 cm in Davos. The straight line shows the mean cumulative trend from 1896–1993. Periods with a higher potential avalanche activity are steeper than the others. No long-term trend or periodicity can be seen in the data.

ular distribution of more or less yearly events, followed again by some years with few events. From 1967 to 1993 the events are clustered in periods of a few years. No long-term trend or systematic pattern can be detected. Comparing the observed avalanche activity with the potential avalanche actitity PAA in Davos (Fig. 4 and 7) it is difficult to see a good coincidence. This is caused by the fact that the effective avalanche activity has been reduced by technical measures.

These calculations could be done for Davos only, because no sufficiently long snow records exist at other stations.

4. Conclusion

There is strong evidence that the mean potential avalanche activity (PAA), at least for the Davos area, has remained the same for the past 96 years. Periods of more or less intensive PAA could be detected, but they show no systematic trend or periodicity. Using a database for destructive avalanches in Switzerland the temporal and spatial damage patterns could be visualized during the past 50 years. It is probable that the extensive protective measures are helpful and reduce the number of destructive avalanches, although the land use in the mountainous areas of Switzerland has increased rapidly. The spatial distribution of the damage patters shows that an avalanche forecast needs spatially well resolved weather data such as snowfall intensity, wind and snow depth. In order to enhance the statistical modelling of destructive avalanches a great additional effort is necessary.

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