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Temporal Trend and Spatial Distribution of Avalanche Activity during the Last 50 Years in Switzerland

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Abstract. Avalanche observations are an important factor for operational avalanche warning and the main parameter to carry out an objective verification of the avalanche bulletin in retrospect. For the first time, a 50-year long series of avalanche activity data of 84 Swiss avalanche observation stations is analysed and discussed. After careful data preparation a regional avalanche activity index (RAAI) for seven snow-climatological regions of Switzerland was developed. Using different statistical descriptors, we were unable to detect a long-term change in avalanche activity, which stands in contrast to a significant increase of winter precipitation. The comparison of the RAAI with a comprehensive database for destructive avalanches (DADB) resulted in a low correlation. This shows clearly the difficulties involved in determining a good measure for specifying the true avalanche activity. Depending on the degree of the avalanche activity DADB and avalanche observations represent the avalanche activity differently and overlap. Suggestions are given for the improvement of the ongoing avalanche observation programme in order to achieve an overall consistent and reliable data set in future.

Key words: avalanche, avalanche activity, avalanche observation, climate change, data quality, destructive avalanche, Switzerland

1. Introduction

Snow avalanches are a major natural hazard in the Swiss Alps. The dense population, the many transit roads and more than 100 large ski areas create a high potential for damage to people, settlements and infrastructures. Thus, the observation of avalanche activity is an important tool for a successful risk management. Laternser and Pfister (1997) compiled historical sources from earlier centuries describing catastrophic avalanche events and reconstructed their meteorological causes. Towards the end of the 19th century avalanches became a major concern for the forestry service as a result of the increasing awareness and importance of natural hazards. Coaz (1889) organized the first detailed survey of avalanche damage from the exceptional winter of 1887/88 and encouraged over decades the compilation of avalanche data by the forestry districts. This resulted in a first extensive avalanche register including a Swiss map with 19,000 avalanche tracks (Coaz, 1910); however, the register has been lost since then. Also the Swiss cantonal reinsurance companies took an interest in natural hazards and engaged Lanz-Stauffer and Rommel (1936) to compile the property damages caused by natural disasters (including avalanches) since 1850. This compilation focuses on monetary aspects, rarely giving details about the actual avalanche events. During the years 1920 to 1989 the "Lawinenatlas Uri" [avalanche atlas of the canton of Uri] was set up with chronological lists of events and mapped avalanche tracks in the scale 1:25,000 (Oechslin, 1989, 1992). This remarkable work gives details of all major avalanches in this small Swiss canton, a region of high avalanche activity. The bibliography drawn up by Laternser and Schneebeli (1995) contains numerous more sources describing early avalanche events prior to 1950 and Schneebeli *et al.* (1998) comprise the most up-to-date lists of avalanche data from the 15th century to 1993. Since the 1950s, avalanche data was systematically collected by the Swiss Federal Institute for Snow and Avalanche Research (SLF). There are two main types of data: The Avalanche Observations (AO), originating from a network of up to 84 snow and avalanche observation stations, provide data of general avalanche activity (number, size and impact), including the specification of the triggering mechanism, avalanche type and various other parameters characterizing the starting conditions (SLF, 1989). The Destructive Avalanches Database (DADB), compiled from the extensive SLF-archives, contains data of more than 10,000 individual avalanches causing property damage or affecting people. The period 1947–1999 is spatially and temporally well covered. Additionally, there are also sporadic entries from earlier times, especially of winter 1887/88 (Laternser *et al.*, 1995, 1998).

There is no international standard for reporting avalanche events and every country has its own approach with more or less subjective judgement involved. McClung and Schaerer (1993, Appendix D) give a comprehensive review of the Canadian and U.S. reporting system. Whereas the system used in Canada is based on estimated potential destructive effects (McClung and Schaerer, 1981; CAA, 1995), in the United States avalanches are classified using five sizes relative to how large a given event is with respect to the historical record of occurrences on a given path (Perla and Martinelli, 1976). Avalanche data following the U.S. classification scheme are accessible in the Westwide Avalanche Network database for about 40 ski stations in the western United States mountain ranges with the majority of sites having at least ten years of complete data, and were recently used to draw up a revised snow avalanche climatology of the western United States (Mock and Birkeland, 2000). Most alpine countries have similar avalanche observation concepts based on the Swiss system, stating number and/or size of avalanches (Chamonix, 1999). In Austria every federal state maintains about 10–20 stations following similar guidelines (e.g., Amt der Tiroler Landesregierung 1994). However, before 1991 different federal states had partly different observation regulations in operation since the 1960s (M. Staudinger, pers. comm., Jan. 2001). In Italy the number and size of avalanches is reported after the same code as in Switzerland, but without considering the impact (Cagnati, 2001). The different regions work since 1983 with a standardized code and today 149 manned observation stations are in operation (A. Cagnati, pers. comm., Feb. 2001). In France a code specifying only the number of avalanches is used, giving no details about size and impact of avalanches (Coléou and Gendre, 1994). Observations were carried out at up to 150 stations for at least 10–20 years (E. Martin, pers. comm., Jan. 2001). The same code is also used in Spain (Pyrenees). Since 1936 and over the following decades in Russia and the former Soviet Union several dozen snow and avalanche observation stations were established with a remarkably broad avalanche observation programme (Bozhinskiy and Losev, 1998, p. 38ff). The station's surroundings were regularly checked for fresh avalanches with the volume of the deposited avalanche snow being a key parameter to be recorded (P. Chernouss, pers. comm., March 1997). These extensive long-term snow and avalanche observations were used for deriving statistical avalanche forecasting rules (Kondrashov, 1991), for climatological surveys (Severskiy and Zichu, 2000) and are extremely valuable input for modern avalanche warning models (Laternser, 2000).

Whereas the Swiss avalanche observations comprise general information of the avalanche activity on single observation spots, the DADB provides area-wide detailed information on individual avalanches. The DADB was used by Schneebeli *et al.* (1998) for extensive studies concerning the interactions between climate, avalanches and technical measures (see also Laternser and Schneebeli, 1996; Schneebeli *et al.*, 1997). The study could not detect an increasing or decreasing trend in the avalanche activity during the past 100 years. However, the number of fatal accidents with people in residential houses in permanent settlements is significantly declining, whereas accidents with ski mountaineers and off-piste skiers and snowboarders are increasing (Tschirky *et al.*, 2001).

This study analyses for the first time the 50-year long series of Swiss avalanche observations (AO) and discusses possibilities and limitations of their practical use. Although the avalanche observation programme was initially launched only for the short-term use for the operational avalanche warning, the data was continuously stored in a database and is nowadays also used for other purposes, such as for the improvement of forecasting models and for climatological evaluations. First, the AO data structure is described and illustrated. Second, an automatic quality control algorithm to select reliable observation stations is presented and an approach is made to spatially visualize the quality-weighted data by means of geostatistical kriging. Third, a regional avalanche activity index (RAAI) is created in order to show the temporal trend as well as the spatial distribution of the regionalized avalanche activity. Fourth, the AO of individual stations and the RAAI are compared with the DADB. Finally, the applicability of the avalanche observations in their present form is discussed and suggestions are presented towards an improved observation programme in order to achieve consistent and reliable data.

2. Description of Data

Avalanche Observations (AO): During the winter months (October to May) daily records of the avalanche activity are available through the SLF-observation stations on an increasing network since the 1950s (Figure 1, Table I). In total 84 stations have electronically accessible records, 74 stations were active in 1999 and 46 stations have long-term data series of 30 years or more (U. Stöckli, pers. comm., Dec. 2000). The avalanche observations are part of an extensive observation programme covering snow and weather parameters as well as an avalanche hazard estimation. Five avalanche parameters are observed, each subdivided by 10 codes (SLF, 1989):

- triggering mechanism (natural/human release, artificial by skier/firing/snow cat, etc.)
- avalanche type (slab/loose snow, dry/wet, surface-layer/full-depth avalanche, etc.)
- slope direction of starting zone (N, E, S, W, sunny/shady, lee/windward slopes, etc.)
- elevation of starting zone (below/above certain elevation zones)
- number, size and impact (Avalanche Index L5, see Table II).

For general avalanche activity the Avalanche Index L5 (number, size and impact) is of primary interest and will be used in this paper. However, as can be seen in Table II, L5 does not have a purely ordered scale, but a mixed ordered-categoric scale. This leads to serious problems determining the "magnitude" of the natural avalanche activity and the categoric part of the scale (L5-codes 6–9) must be transformed into the ordered scale of the L5-codes 0–5. This will be further discussed in Section 3.2.

Another problem interfering with the consistency of the data series is a change of the coding system in the winter of 1987/88. Despite the fact that the old codes were converted into the new ones as far as possible, this could not be done one-to-one. The new L5-codes 2–3 (few and several medium avalanches without damage) did not exist in the old coding system; therefore "medium" avalanches had to be subjectively divided either into "small" or "big" avalanches. Consequences out of this inconsistent survey will be mentioned in Sections 4.2 and 4.4.

Finally, L5 time-series plots sometimes show serious quality concerns of the observation data itself. Whereas some stations have hardly any observations, some others show a plausible frequency distribution of occurred avalanches and for individual stations, periods of good avalanche observations can take turns with bad years. Quality breaks appear often after an exchange of the observer, which shows the subjectivity of observations that can not be measured with a standard instrument. Thus, avalanche observation data need extensive preprocessing to become statistically treatable as a whole (Section 3.1). This is different to actual forecasting, where "missing values" are deemed less important.

In the following, the inconsistent data quality is exemplarily demonstrated by comparing the two neighbouring observation stations of Münster and Ulrichen,

Table Ia. Details of the 46 long-term avalanche observation stations with more than 30 years of observations, including the mean of the annual avalanche observation quality (range: 0 [implausible] − 2 [plausible]). * behind the observation period indicates that whole years are missing; bold numbers mark stations no longer in operation or with no data in 1999.

Code	Station name	Altitude (m a.s.l.)	Observation period	Years with observations	L5-Quality (mean)
1HB	Hasliberg	1830	1960–1999*	37	0.2
1MR	Mürren	1660	1951–1999	49	1.2
1GB	Grindelwald Bort	1570	1951–**1991**	41	1.4
1MN	Moleson	1520	1965–1999	35	1.3
1SM	Saanenmöser	1390	1954–1999	46	0.5
1AD	Adelboden	1350	1954–1999	46	1.7
1WE	Wengen	1310	1969–1999	31	1.4
1LS	Leysin	1250	1953–**1995**	43	0.3
1GS	Gsteig	1195	1954–1999	46	1.5
2TR	Trübsee	1770	1952–1999	48	1.6
2AN	Andermatt	1440	1952–1999	48	1.4
2ME	Meien	1320	1954–1999	46	1.2
2ST	Stoos	1280	1952–1999	48	0.7
2SO	Sörenberg	1160	1953–1999	47	0.4
2OG	Oberiberg	1090	1954–1999	46	0.1
3BR	Braunwald	1340	1954–1999	46	2.0
3UI	Unterwasser-Iltios	1340	1958–1999	42	0.8
3FB	Flumserberg	1310	1958–1999	42	0.0
3W	Schwägalp	1290	1967–1999*	36	1.1
3MG	St. Margrethenberg	1190	1954–**1994***	40	0.0
4SF	Saas Fee	1790	1952–1999	48	0.9
4BP	Bourg-St-Pierre	1610	1952–1999	48	0.8
4ZE	Zermatt	1600	1952–1999	48	0.2
4MO	Montana	1590	1952–**1998***	34	0.2
4GR	Grimentz	1570	1954–1999	46	0.8
4MS	Münster	1410	1952–1999	48	0.6
4WI	Wiler	1400	1952–1999*	46	0.2
4UL	Ulrichen	1350	1953–1999*	46	0.9
5AR	Arosa	1820	1954–1999*	43	1.4
5BI	Bivio	1770	1953–1999*	45	1.1
5ZV	Zervreila	1735	1960–1999*	31	0.1
5SA	St. Antönien	1510	1952–1999	48	0.9
5SP	Splügen	1460	1952–1999	48	1.4
5OB	Obersaxen	1420	1952–1999*	31	0.2
5SE	Sedrun	1420	1968–1999*	31	0.9

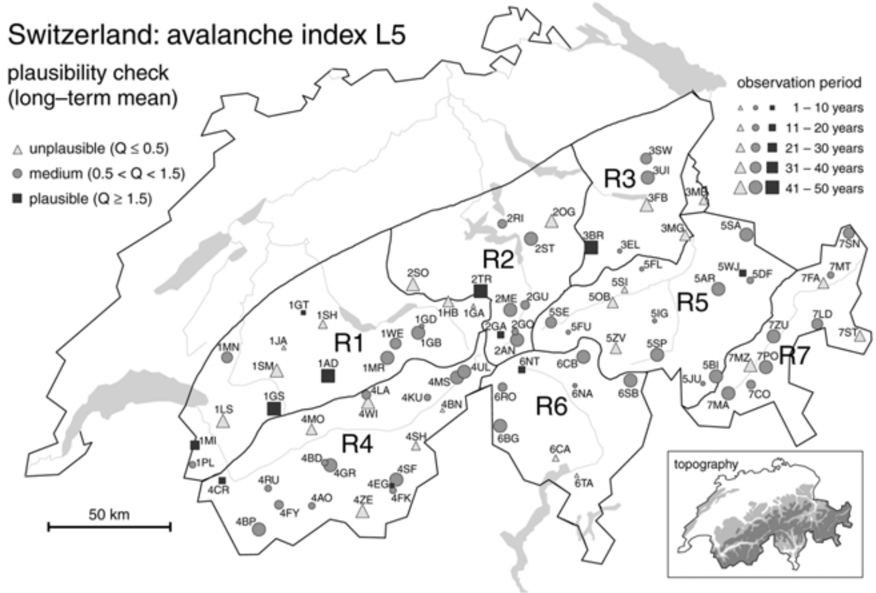

Figure 1. Map of Switzerland with the SLF avalanche observation station network (station labels in Table I). The dot size indicates the length of the observation period. Also shown is the station rating according to the quality of the avalanche observations (mean of the annual classification; see later in the text). Of the 46 long-term stations with data series longer than 30 years 9% are classified "plausible", 59% "medium" and 32% "implausible". The result for all 84 stations is 13% "plausible", 58% "medium" and 29% "implausible". R1–R7 refer to the seven main snow-climatological regions. The inset shows the topography (white: <1000 m, light grey: 1000–2000 m, dark grey: >2000 m a.s.l.).

Table Ia. Continued

Code	Station name	Altitude (m a.s.l.)	Observation period	Years with observations	L5-Quality (mean)
6SB	San Bernardino	1640	1952–1999	48	1.1
6BG	Bosco/Gurin	1490	1952–1999	48	1.1
6CB	Campo Blenio	1190	1953–1999	47	0.7
7MZ	St. Moritz	1890	1954–1999*	45	0.4
7PO	Pontresina	1840	1953–1999	47	1.0
7MA	Maloja	1800	1952–1999*	47	1.2
7SN	Samnaun	1750	1960–1999	40	1.2
7FA	Ftan	1710	1953–1999*	34	0.3
7LD	La Drossa	1710	1968–1999	32	1.1
7ZU	Zuoz	1710	1952–1999	48	0.8
7ST	Sta. Maria	1400	1968–1999	32	0.5

Table Ib. Details of the 38 short-term avalanche observation stations with less than 30 years of observations, including the mean of the annual avalanche observation quality (range: 0 [implausible] − 2 [plausible]). * behind the observation period indicates that whole years are missing; bold numbers mark stations no longer in operation or with no data in 1999.

Code	Station name	Altitude (m a.s.l.)	Observation period	Years with observations	L5-Quality (mean)
1GD	Grindel	1950	1992–1999	8	1.1
1PL	Planachaux	1780	1980–1999	20	1.4
1SH	Stockhorn	1650	1972–1999*	25	0.4
1JA	Jaun	1520	1990–1999	10	0.1
1GT	Gantrisch	1510	1993–1999	7	1.9
1MI	Morgins	1380	1974–1999	26	1.6
1GA	Gadmen	1190	1996–1999	4	0.0
2GA	Göscheneralp	1750	1989–1999	11	1.5
2RI	Rigi Scheidegg	1640	1975–1999	25	1.0
2GO	Göschenen	1110	1969–**1987**	19	0.7
2GU	Gurtnellen	940	1969–**1992**	24	1.4
3EL	Elm	1690	1990–1999	10	1.3
3MB	Malbun	1610	1972–1999	28	0.3
4FK	Felskinn	3000	1980–**1992**	13	1.3
4EG	Egginer	2620	1993–1999	7	1.6
4RU	Les Ruinettes	2250	1980–1999*	19	1.3
4KU	Kühboden	2210	1989–1999	11	1.3
4BD	Bendolla	2160	1989–1999	11	1.4
4SH	Simplon Hospiz	2000	1963–1999*	26	0.3
4LA	Lauchernalp	1980	1975–1999	25	0.6
4AO	Arolla	1890	1989–1999	11	0.7
4CR	La Creusaz	1720	1989–1999	11	1.5
4FY	Fionnay	1500	1953–1999*	29	1.4
4BN	Binn	1410	1992–1999*	7	0.0
5WJ	Weissfluhjoch	2540	1984–1999	16	1.6
5JU	Juf	2120	1995–1999	5	1.4
5FL	Flims Naraus	1850	1991–1999	9	1.3
5IG	Innerglas	1810	1993–1999	7	0.7
5DF	Davos Flüelastrasse	1560	1984–1999	16	1.2
5FU	Fuorns	1480	1996–1999	4	1.2
5SI	Siat	1280	1953–**1997***	15	0.0
6RO	Robiei	1890	1966–1999*	29	1.2
6CA	Cardada	1620	1968–**1991***	20	0.0
6NA	Nara	1450	1976–**1985**	10	1.3
6TA	Tamaro	1450	1995–1999	5	0.4
6NT	Nante	1420	1984–1999	16	1.6
7CO	Corvatsch	2690	1973–1999	27	1.3
7MT	Motta Naluns	2150	1983–1999	17	1.3

Table II. SLF avalanche observation codes for Avalanche Index L5 (number, size and impact). The first appropriate code from top to bottom has to be selected. In the database, "observation impossible" (/) can not be distinguished from "no observation" ( ); both are represented as "missing values" (NA).

L5	Number, size and impact of avalanches
/	observation impossible
0	no avalanches
9	extent unknown
8	avalanche with fatalities
7	avalanche with caught or buried persons
6	avalanche with property damage (buildings, forest, road, railway)
5	several (more than two) big avalanches, without damage
4	few (one or two) big avalanches, without damage
3	several (more than two) medium avalanches, without damage
2	few (one or two) medium avalanches, without damage
1	few or several small avalanches, without damage

which are situated in the Upper Valais only 4 km apart from each other. Both stations are located on very similar aspects and with about the same visible horizon (cf. Figure 1). Münster served as an observation station since winter 1951/52, Ulrichen started one year later. The stations were slightly moved several times and the observers were exchanged occasionally. Analysing the quality of the avalanche observation time series (Avalanche Index L5) reveals big differences between both stations, but shows some parallels to single observer periods.

Münster (Figure 2): The station was slightly moved in 1957, 1980 and 1986, but always remained in the southern outskirts of the village. The observers changed in 1980 and 1986. During the first few winters of observation avalanches were reported only occasionally. After the relocation of the station in 1957 the records became gradually more frequent and after a few more years (of gaining experience?) they show generally – with an odd exception (1964) – a plausible frequency distribution. From about 1972 on, the avalanche observations decreased again to an unrealistic minimum. Also the observer exchanges in 1980 and again in 1986 did not improve the situation: the avalanche observations remained on a minimum up to very recently. Only in the last three years has the situation improved again.

Ulrichen (Figure 3): The station was moved only once, in 1966, after a winter of no observations at all. Until 1965 the station was located on the eastern edge of the village and served by a private person. Since 1966 the observations were carried out by the frontier guard always at the same location in a flat open place some-

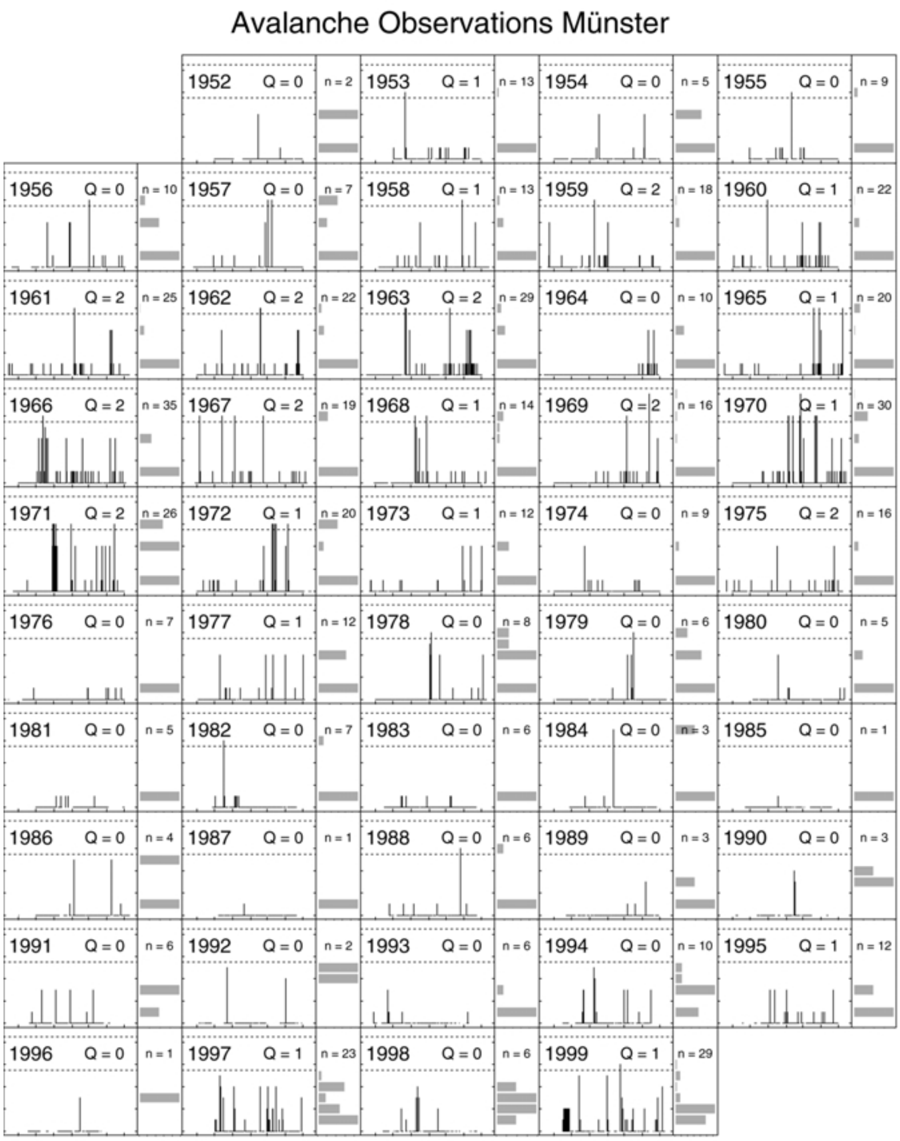

Figure 2. Avalanche Index L5 (impact, number and size) of Münster for the winters 1951/52–1998/99. *Q* is the automatically classified data quality (0 = implausible, 1 = medium, 2 = plausible. *n* is the total number of days with observed avalanches (L5 > 0). For further details see Figure 4.

what away from the village, but the actual persons in charge for the observations were exchanged in 1978, 1987 and 1993. During the period of the first observer virtually no avalanches were recorded. After the new set up of the observation station in 1966, the avalanche observations became generally more frequent but year-to-year variations were considerable. Some years show only the lowest code (small avalanches) throughout the whole winter, but nearly every day, whereas some other years show very few avalanches, and only a few winters seem to have realistic observations. This was probably caused by many different persons actually in charge of the job during this period. From 1978 on two defined persons from the frontier guard shared the duty and the observations improved slightly. Since 1987, when the next observer took over, the records were rather excellent: generally plenty of avalanches with a plausible frequency distribution from small to large and destructive. With the following observer, from 1993 on, the avalanche observations tend to be poorer again.

3. Methodology

3.1. STATION RATING ACCORDING TO THE QUALITY OF THE AVALANCHE OBSERVATIONS

By visualizing AO data and especially by comparing nearby stations, it was soon realized that the avalanche observations are highly variable in their quality. However, our means to confirm the reliability are very limited. We can compare the AO with the DADB, but this is only practicable for destructive avalanches. Therefore we developed a plausibility check for Avalanche Index L5 which is based on the annual number of observed avalanche days, the annual frequency distribution and the longest, annual sequence of missing data. The plausibility check, which is implemented as a quality control algorithm programmed in S-Plus (StatSci, 1993), determines for every station and every winter a quality estimate (Q) using three classes: 0 (implausible), 1 (medium) and 2 (plausible). The following variables are used: S is the total number of avalanche days (L5 $>$ 0) during the whole winter. q_{10}, q_{25} and q_{50} are the 10%-, 25%- and 50%-quantiles of the annual sums of observed avalanche days of all winters with more than 10 avalanche days. The frequency distribution is judged on the number of levels (different L5-codes) and the relative length of the different levels of the histogram. In this sense a plausible histogram shows small, harmless avalanches most frequently, and large, destructive avalanches, possibly with deadly consequences, least frequently (Figure 4). NA stands for missing values. Expressed as a pseudo code the criterions look as follows (for criterions labeled with * see additional details further below):

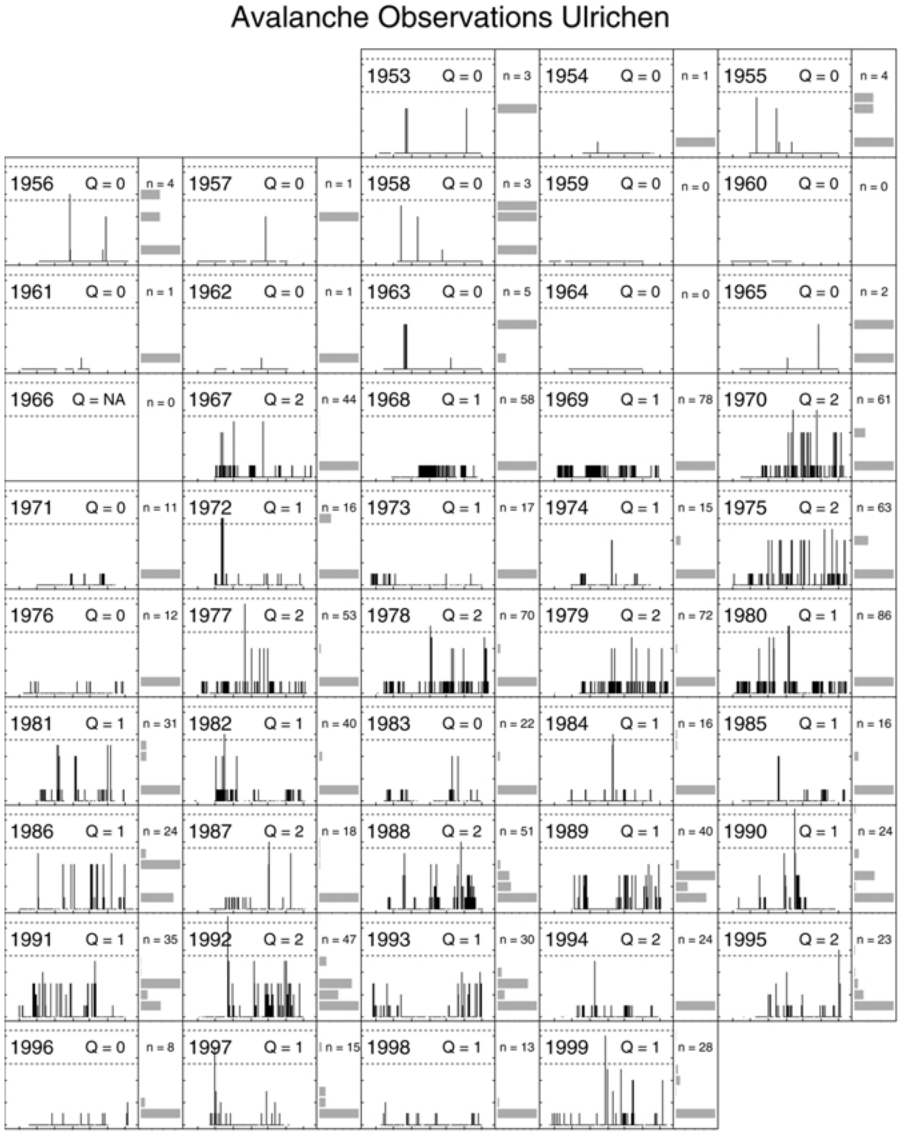

Figure 3. Avalanche Index L5 (impact, number and size) of Ulrichen for the winters 1952/53–1998/99. *Q* is the automatically classified data quality (0 = implausible, 1 = medium, 2 = plausible. *n* is the total number of days with observed avalanches (L5 > 0). For further details see Figure 4.

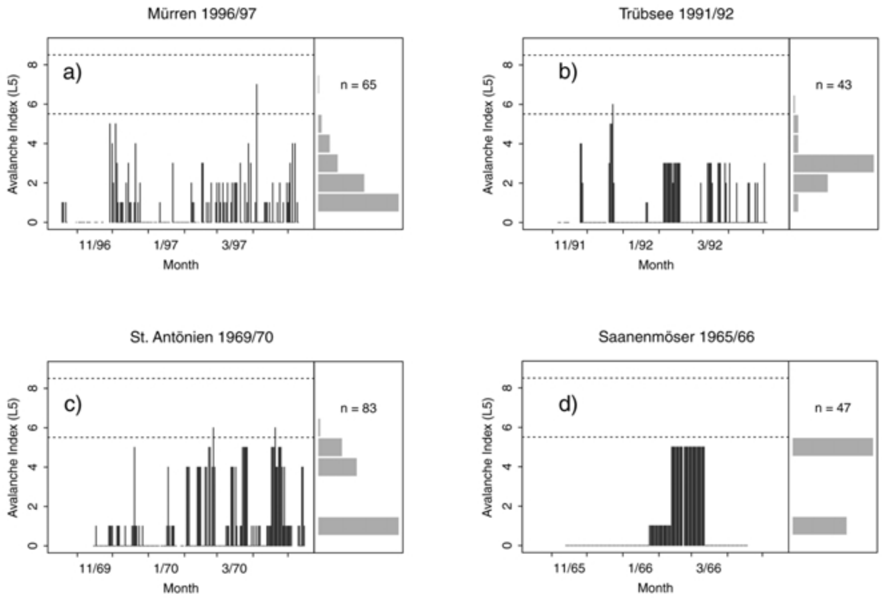

Figure 4. Four examples of annual time-series of Avalanche Index L5 (number, size and impact). The left part of each plot shows L5 in daily resolution from mid October to mid May. The units of the y-axis (L5-codes 0–9) are explained in Table II; the horizontal, dashed lines point up the categoric L5-codes 6–8 (human and property damage). The right part of each plot shows the frequency distribution (histogram) of L5 and *n* is the total number of days with observed avalanches (L5 $>$ 0). Whereas (a) and (b) show years according to the new code, (c) and (d) show years prior to the code change in 1987/88, when L5-codes 2–3 did not exist yet. (a) Mürren, winter 1996/97, and (c) St. Antönien, winter 1969/70, show both a plausible frequency distribution: small avalanches are most frequent, bigger avalanches are less frequent and destructive avalanches least frequent. On the other hand (b) Trübsee, winter 1991/92, and (d) Saanenmöser, winter 1965/66, show both implausible histograms: Trübsee shows hardly any small avalanches compared to numerous medium avalanches and in Saanenmöser until late January no avalanches were observed at all, then for about three weeks every day small avalanches and from mid February to mid March every day several big avalanches (including one day of no observation). Finally, all of a sudden no avalanches were observed anymore.

0)	if(all(AO) = NA)	$\rightarrow$ Q = NA [no observations $\rightarrow$ no classification!]	
1)	if(S $\leq$ 10)	$\rightarrow$ Q = 0	
2)*	if(S $<$ q_{10})	$\rightarrow$ Q = 0	
		but if histogram has	
		• at least two levels	
		• and higher level is at most +1 of next lower level	$\rightarrow$ Q = 1
3)*	if(q_{10} $\leq$ S $<$ q_{25})	$\rightarrow$ Q = 1	
		but if only one level	$\rightarrow$ Q = 0
		or if S $>$ 20 and histogram has	
		• at least two levels	
		• and higher level is at most +1 of next lower level	
		• and lowest level (L5-code 1) is most frequent	$\rightarrow$ Q = 2

4)	if($q_{25} \leq S < q_{50}$)	$\rightarrow Q = 1$		(1)
		but if histogram has		
		• at least two levels		
		• and higher level is at most +30% of next lower level		
		• and lowest level (L5-code 1) is most frequent	$\rightarrow Q = 2$	
5)	if($S \geq q_{50}$)	$\rightarrow Q = 1$		
		but if histogram has		
		• at least three levels after 1988 (two levels for earlier years)		
		• and higher level is at most +50% of next lower level		
		• and lowest level (L5-code 1) is most frequent	$\rightarrow Q = 2$	
6)*	if more than 7 successive missing values		$\rightarrow Q \leq 1$	
	if more than 20 successive missing values		$\rightarrow Q = 0$	

The idea behind is that for a given station every winter is rated relatively depending on the stations own long-term distribution and not by absolute values. Only criterion 1 sets an absolute lower limit for S and assumes that a station with less or equal than 10 avalanche days per winter contains implausible data ($Q = 0$). Thus, an unfair misclassification could happen for low-elevated stations with low avalanche activity surroundings. However, such stations will be of not much use for further analyses concerning the avalanche activity anyway.

The quantile calculation for criterion 2–5 has two empirically determined special conditions built-in dealing with very low and very high quantile values: First, in order to avoid that stations with few observations get very low quantiles, and thus years on the upper end of the quantile distribution will get an overestimated high rating, only years with more than 10 avalanche days are considered for the quantile calculation. Second, for stations with plenty of observations and $q_{10} > 20$, q_{10} will be set back to 20 in order to prevent that those winters on the lower end of the quantile distribution will not necessarily get a low classification, just because these years fall below the 10%-quantile limit.

Finally, criterion 6 is an "emergency brake" at the end of the algorithm in case that many missing values interrupt the observation series. Relevant for criterion 6 is the number of consecutive missing values during the period between the first and the last avalanche observation ($L5 > 0$), but earliest from 15 December and latest until 15 April. Years with many missing values at the beginning or the end of the winter are not affected by this criterion.

3.2. TRANSFORMATION FROM CATEGORIC TO ORDERED DATA

The Avalanche Index L5 has a mixed ordered-categoric scale (Table II). Whereas the lower codes 0–5 are of increasing order indicating the general avalanche activity (number and size of avalanches), the codes 6–8 describe only the impact of the avalanche(s). A single, small avalanche (code 1) can close a road (code 6) or even kill a skier (code 8). From the point of view of the natural avalanche activity, a code 6–8 does not necessarily imply that the event was of higher magnitude than codes 1–5. Even within the codes 6–8 there is no clear order. Code 8 may stand for a catastrophic avalanche causing severe damage and killing several people, but possibly it stands for a small slide killing an unfortunate skier. Code 7 is possibly a harmless slide partly burying a skier, of far lesser magnitude than an event of code 5, but it could also be an avalanche of code 6, which even buried people. Also the highest code of the scale (code 9, avalanches of unknown extent) does not say anything about the magnitude of the avalanche event and thus, all codes > 5 must be transformed into the same ordered scale as codes 0–5 to be used for a proper determination of the avalanche activity. An alternative would be to omit all data with codes > 5 for further analyses, but then the useable data population would become very small in many situations.

The only feasible solution of this problem is to replace codes > 5 by a quality-weighted average of neighbouring stations with codes between 0–5. The Swiss Alps are traditionally divided into seven snow-climatological regions (cf. Figure 1) and every region contains about ten observation stations. The idea is to calculate a quality-weighted regional average of all stations with avalanche observation codes ≤ 5, and then to replace codes > 5 by two substitute classes depending on this average. The quality-weighted mean (M1) is calculated using the formula

$$\mathrm{M1} = \sum (\mathrm{L5}_{[0\text{–}5]} \times \mathrm{QW}) / \sum \mathrm{QW} \tag{2}$$

with $\mathrm{L5}_{[0\text{–}5]}$ = L5-codes ≤ 5 and QW = quality weights. For the quality weights the original three quality levels 0, 1 and 2 are transformed to 0.2, 1 and 5. For the mean calculation a reliable station (Q = 2) will weigh five times higher, a medium station (Q = 1) will remain with weight one and an unreliable station (Q = 0) will be weighted only 0.2. If M1 > 3, then it is likely that L5-codes > 5 (property damage, buried or killed people) mean rather big avalanches and will be replaced by 5 (several big avalanches). If M1 ≤ 3, then it is more likely that L5-codes > 5 mean either a skier accident or only a small destructive avalanche and will be replaced by 2 (few medium avalanches). In the case for a certain date and region no observations with L5-codes ≤ 5 are available (e.g., only missing values), then L5-codes > 5 will be replaced by 3 (several medium avalanches), which is the mean between 1–5.

3.3. REGIONAL AVALANCHE ACTIVITY INDEX (RAAI)

A good method for the spatial visualization of geostatistical data is kriging (Cressie, 1993). The method is based on the principle that neighbouring stations usually are correlated to a high degree than stations further apart. However, because of the marked quality differences between the stations, neighbouring stations often

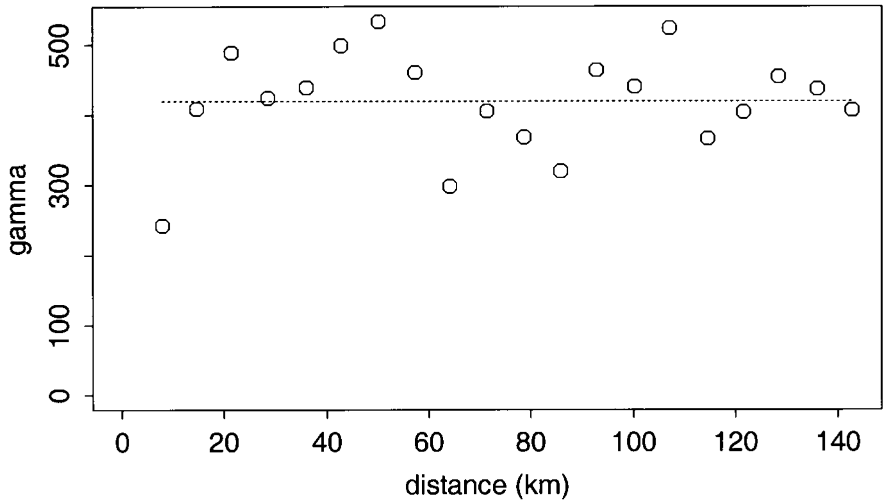

Figure 5. Empirical variogram of avalanche observation data (number of days with observed avalanches) from winter 1998/99. The semivariance (gamma) is rapidly increasing and after the first lag stations are spatially uncorrelated.

do not show much similarities, and the spatial data distribution looks rather like a random distribution. Therefore it is not possible to fit a reasonable theoretical variogram model to the empirical variogram, which would be necessary for the incorporation into the kriging equations (Figure 5). In addition, data for kriging must be of ordered scale, and it is questionable to use the transformed L5-codes > 5 (after the method shown above), because this transformation is based on the average of predefined regions, and the results can not be used in the distance-based kriging algorithm. For these reasons kriging was not further used, but another approach was chosen to regionalize the avalanche activity.

With the quality-weighted and transformed AO data, a Regional Avalanche Activity Index (RAAI) for the seven traditional snow-climatological regions was developed. The formula looks similar to Equation (2), but this time all L5-codes are considered, including the transformed original codes > 5:

$$\mathrm{RAAI} = \sum (\mathrm{L5}_{\mathrm{all}} \times \mathrm{QW}) / \sum \mathrm{QW} \tag{3}$$

with $\mathrm{L5}_{\mathrm{all}}$ = L5-code of the original codes ≤ 5 and the transformed, original codes > 5. QW are the same quality weights as in Equation (2). Thus, the maximum range of the RAAI is 0–5.

Because there are often only very few reliable stations available in a given region, only stations with a plausible frequency distribution are considered for the calculation of the mean. During periods of high avalanche activity often no observations are made, either because the terrain was not visible or the observer was unable to do it. The database makes no difference between "no observation" and "observation impossible"; both are represented as "missing values". The situation from 20–24 February 1999 shows that during this severe avalanche period only 18 stations (24%) reported avalanche observations every day (from which three stations always reported “no avalanches”, what is extremely unlikely to be true). Fifty stations had one or several days during this period with missing observations, and six stations had no observations at all.

4. Results

4.1. QUALITY CONTROL OF AVALANCHE OBSERVATION STATIONS

With the plausibility check the data quality of all stations can be classified for every winter. Figure 1 shows the mean of the annual ratings together with the length of the observation period. According to this Braunwald (3BR), Trübsee (2TR), Adelboden (1AD) and Gsteig (1GS) are the only long-term stations with excellent avalanche observations. The majority of the other long-term stations (59%) are classified medium, and about one third of all long-term stations show “implausible” avalanche data. The individual station details including the abbreviated labels are shown in Table I.

It can not be expected that an automatic quality check perfectly meets every case and some winters/stations might not be properly classified. But the suggested algorithm is a reasonable approach to get an overview about the plausibility of the avalanche observations just by means of the statistical distribution. Whether the observations truly meet the reality or not can never be verified in retrospect. The only way of getting some indications for this is to compare neighbouring stations (as done in Section 2) or to compare the observations with other avalanche data archives, such as the DADB. This latter approach will be outlined in Section 4.3.

4.2. TEMPORAL DEVELOPMENT OF THE REGIONAL AVALANCHE ACTIVITY

The Regional Avalanche Activity Index (RAAI) does not show a significant long-term change. Whereas the annual RAAI-mean is slightly rising in some regions, the annual RAAI-maximum is rather decreasing. Figure 6 shows for all seven regions the fluctuating curves of the annual RAAI-mean including a lowess-smoother (robust locally linear fit programmed in S-Plus; StatSci, 1993). Large annual fluctuations are typical, but on the whole, most regions remain on a constant level during the past 50 years, except Region 3 and 4. However, Region 3 consists of only seven stations, from which only one (3BR) shows a plausible data distribution (cf. Figure 1) and contributes with a high weight to the RAAI-mean calculation. Thus, the RAAI-mean of Region 3 is clearly dominated by this one single station and follows directly the long-term trend of 3BR, which in fact shows an increase during the last 10–20 years. Region 4 kept an unnaturally low level during the first 20 years (because of many incomplete observations of long-term stations), then rose to a more plausible level and remained rather constant on this up to now.

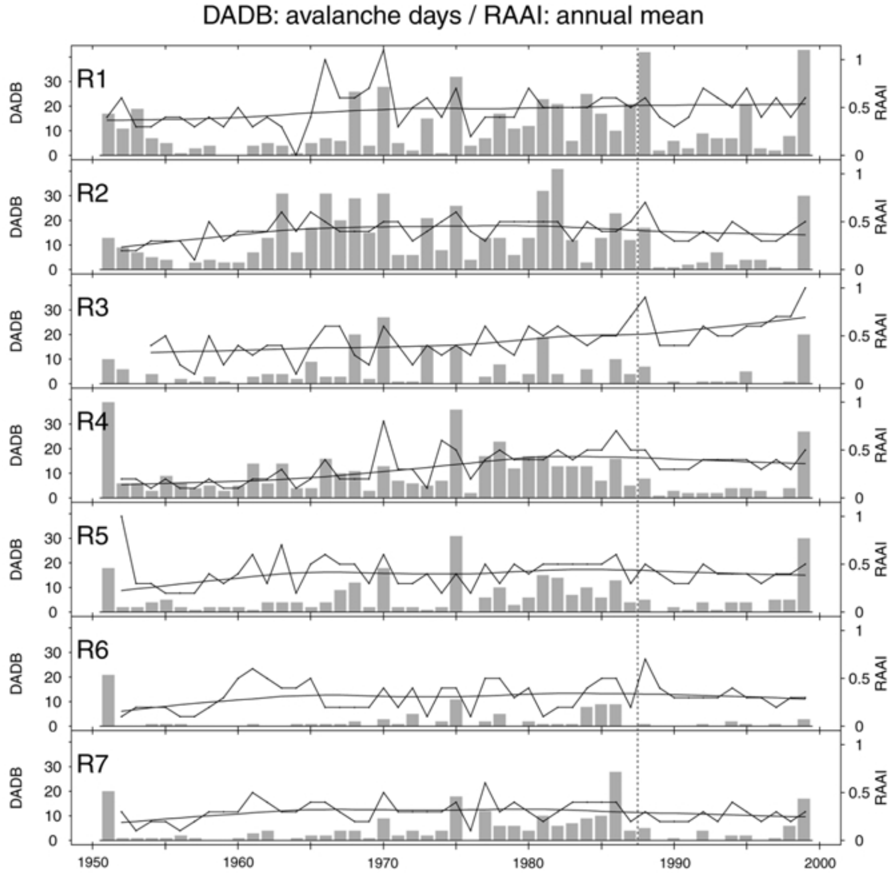

Figure 6. Annual number of avalanche days according to the DADB (bars) and annual RAAI-mean (jagged line) including a lowess-smoother (smooth line) for all seven regions during the period 1951–1999. The dashed line indicates the AO-code change in 1987/88. “Skier avalanches” are excluded from the DADB; only spontaneously released destructive avalanches are shown.

The annual RAAI-maximum shows a slightly more diverse picture (Figure 7). Whereas Region 1 reaches a low point in the 1980s, Region 4 just reaches a high point by then. But generally most regions seem to have observed smaller avalanches during the last 10–15 years. A reason for this may be the change of the coding system in 1987/88, since “medium-seized” avalanches (L5-code 2–3) could be reported. Before that it was only possible to report “small” (code 1) or “big” (code 4–5) avalanches and probably many “medium” avalanches were then reported as “big”, what of course led to a higher RAAI. Finally, the number of days with RAAI > 3 (Figure 8) shows no significant changes. However, it is notable that during the first few decades the annual variations were quite large, but since about 1990 became rather stable.

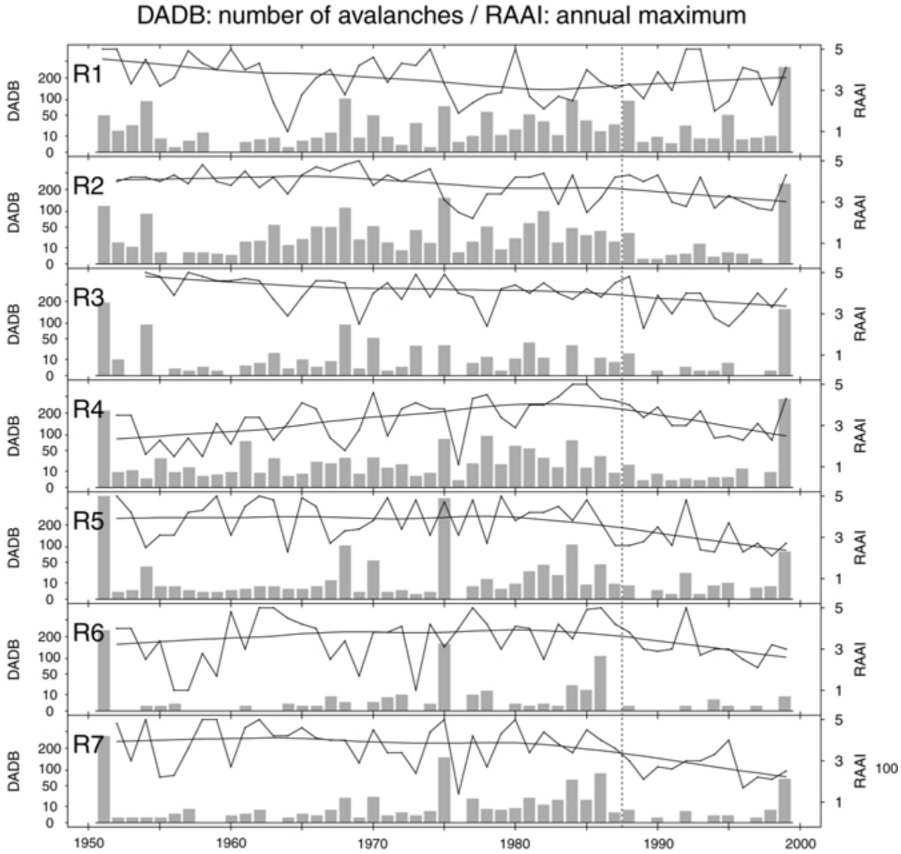

Figure 7. Annual number of avalanches according to the DADB (bars, square-root-transformed scale) and annual RAAI-maximum (jagged line) including a lowess-smoother (smooth line) for all seven regions during the period 1951–1999. The dashed line indicates the AO-code change in 1987/88. "Skier avalanches" are excluded from the DADB; only spontaneously released destructive avalanches are shown.

Additionally and for comparison, Figures 6–8 show the number of avalanche days (Figure 7 the number of avalanches) according to the DADB. The late 1950s/early 1960s and the 1990s (except 1999) were periods with remarkably few destructive avalanches. However, RAAI and DADB are not highly correlated.

4.3. COMPARISON OF AVALANCHE INDEX L5 WITH THE DESTRUCTIVE AVALANCHES DATABASE (DADB)

To check the hypothesis that the intensity of avalanche damage strongly corresponds with the general avalanche activity, the Destructive Avalanches Database (DADB) was compared with the daily Avalanche Index L5. For this purpose selected stations of the greater Gotthard area (the region with the highest ava-

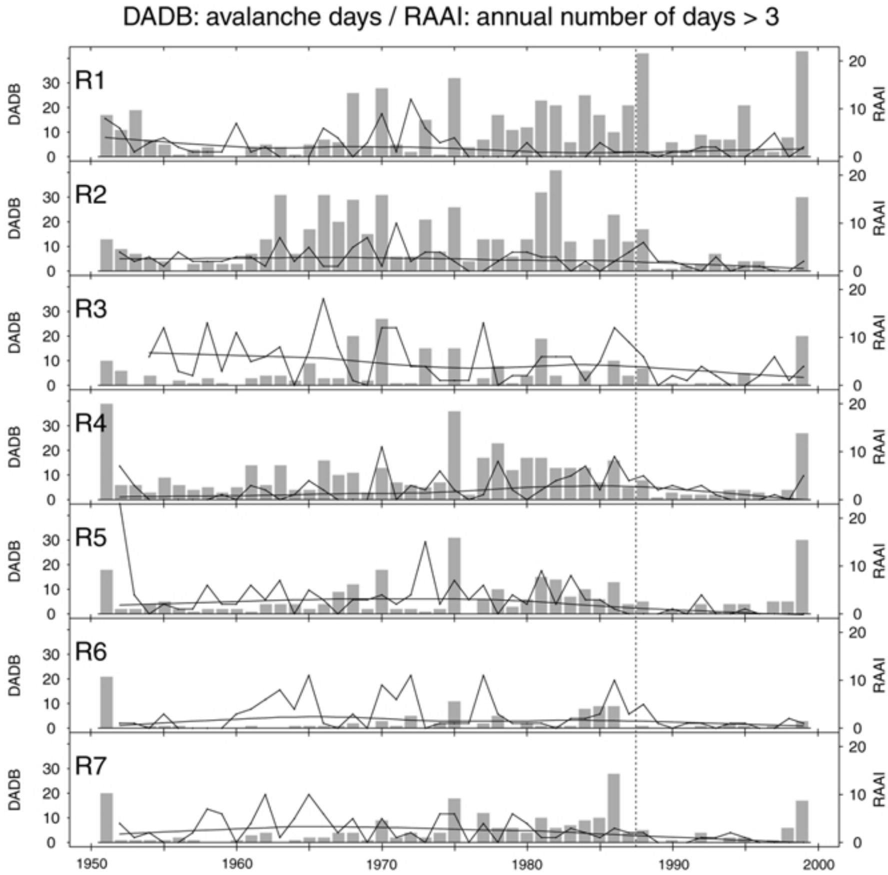

Figure 8. Annual number of avalanche days according to the DADB (bars) and annual number of days with RAAI > 3 (jagged line) including a lowess-smoother (smooth line) for all seven regions during the period 1951–1999. The dashed line indicates the AO-code change in 1987/88. "Skier avalanches" are excluded from the DADB; only spontaneously released destructive avalanches are shown.

lanche frequency) were used. The result is shown with two examples: Andermatt, which seems to have reasonably good avalanche observations (Q = 1 and 2), and Hasliberg, which seems to have rather unsatisfying avalanche observations (mainly Q = 0).

Andermatt: For every winter time series plots of the Avalanche Index L5 were visually compared with the daily number of destructive avalanches from the DADB, which occurred within the community boundaries of Andermatt (six examples are shown in Figure 9). It is obvious that small and harmless avalanches are much more frequently observed than destructive avalanches are recorded in the DADB. Therefore only the coincidence between code 6–8 of the observations (destructive avalanches, buried and killed people; between dashed lines in Figure 9) and the DADB was examined, and as a rough estimate was found to be about 40%. This rather unsatisfactory result can be partly explained by the following reasons: The observer station is situated in close vicinity to the village and the observer has a limited view over the whole Andermatt territory (from where the DADB values were selected). Therefore the observer should rather underestimate the true avalanche activity. Often this can be verified (especially in 1981/82, see Figure 9c), but sometimes also the opposite is the case, and the observer reports avalanches which are not in the DADB. Usually such avalanches turn out to be skiers accidents. Although the observer cannot see the avalanches from his position, he hears about them from colleagues, via radio or from the news, and he promptly reports them in the daily avalanche observations; sometimes even a few days later or when the accidents are quite far away. In a few cases it can be shown that the observer reports accidents, which actually happened in neighbouring valleys up to 10 km away from Andermatt (12 April 1964: four skiers killed in the Fellital; 21 March 1967: five construction workers killed on the eastern side of the Oberalppass; 25 April 1986: one skier killed in the Göschenertal). Another possibility of inaccurate avalanche "observations" may also be that the observer hears from an accident with victims or damages in the surroundings, promptly reports it and afterwards it turns out to be not that serious. For example on 3 January 1979, when a fatal avalanche was reported, but the only accidents in the area during this time was one burying (not killing) three skiers in the ski area above Andermatt, but already on 30 December 1978. All these examples show that even data from stations with plausible observations (Q = 1 or 2) should be treated with care.

Hasliberg: The observation station is situated in the ski area above the village overlooking most of the Hasliberg territory. A rough estimate of the coincidence between the DADB and the avalanche observations comes to about 80%. The reason for this high coincidence is because in most years neither the DADB nor the observations contain any (destructive) avalanches at all, which results in a 100% match. Looking at the topography and the actual damage potential it seems realistic that there are only a few destructive avalanches. This speaks for an accurate database. But how about the avalanche observations? It is unlikely that in a ski area only so few (harmless) avalanches occur as reported. In fact there were more avalanche accidents in the ski area, for example in the 1990s when two accidents with buried people were not reported by the observer (see Figure 10e, f). But a large accident, which happened on 5 May 1990 in a neighbouring valley 13 km to the south and killed seven ski mountaineers, was "observed" and reported three days later after it became public in the media (see Figure 10c)!

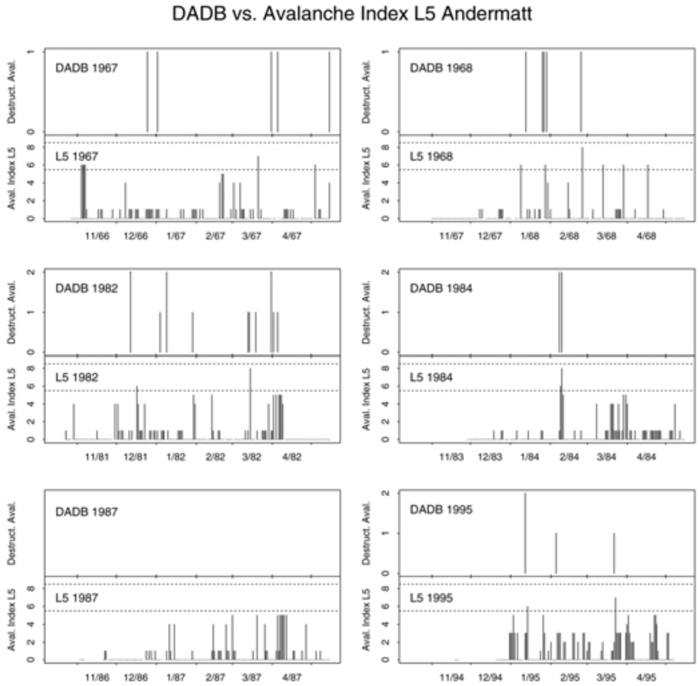

Figure 9. Six winters with daily comparison between the Destructive Avalanches Database (DADB) and Avalanche Index L5 for Andermatt. The upper part of each plot shows the number of destructive avalanches from the DADB (note the different scales!) and the lower part of each plot contains the Avalanche Index L5 (impact, number and size).

- Winter 1966/67: Bad coincidence. The DADB-events are not recorded in the observations and the observed destructive avalanches (code 6) are not in the DADB. Furthermore, the "observed" code 7 (buried person) is likely to be wrong; the nearest avalanche accident around this date was claiming five lives in an other valley 10 km away.
- Winter 1967/68: Mainly bad coincidence. Most of the observed destructive avalanches (code 6) are not in the DADB, except one on 28 January. 26–28 January 1968 was a severe avalanche period affecting large parts of the Swiss Alps. But exactly during this heavy snow fall and avalanche situation for three days (25–27 January) no observations were made. However, the skier accident of 25 February is reported in both the DADB and the observations.
- Winter 1981/82: Mainly bad coincidence. Many destructive avalanches in the DADB, but only one according to the observations. Only the skier accident of 14 March is reported in both the DADB and the observations.
- Winter 1983/84: Good coincidence. The severe avalanche period around the 9 February 1984 is well documented in both the DADB and the observations.
- Winter 1986/87: Good coincidence. Neither the DADB nor the observations show any destructive avalanches.
- Winter 1994/95: Partly good coincidence. The only day with destructive avalanches is shown in both the DADB and the observations. Whereas one skier accident in the close-by ski area is reported by the observer (22 March), an other ski-touring accident further away is not (5 February). However, the February accident can not be expected to be seen by the observer.

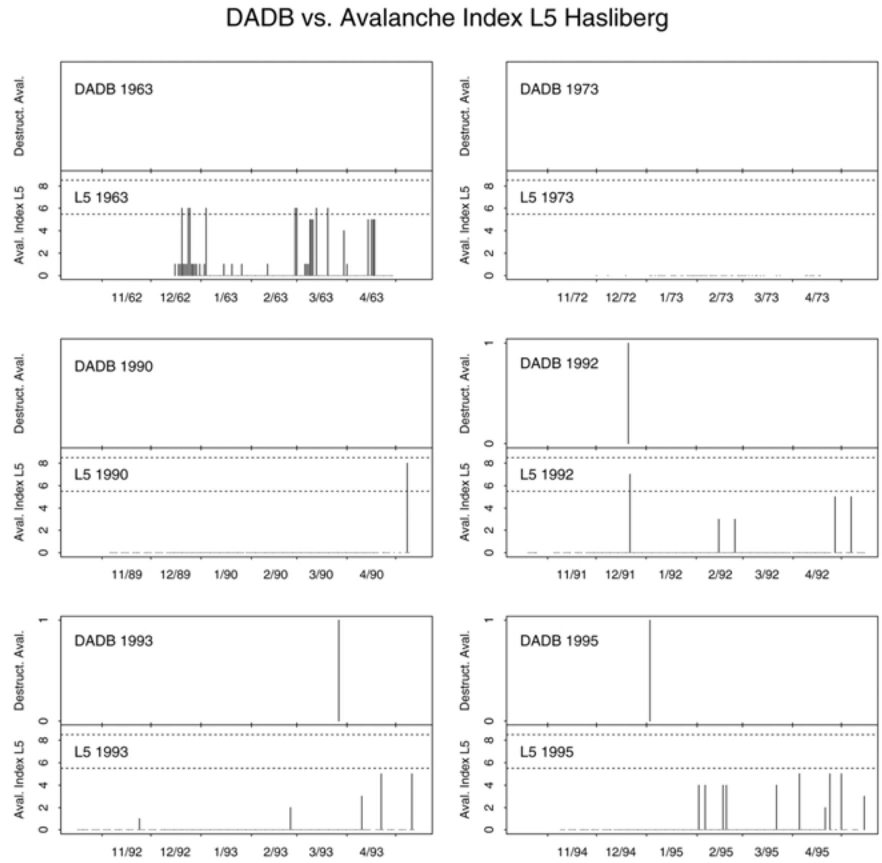

Figure 10. As Figure 9, but for Hasliberg.

- Winter 1962/63: Bad coincidence. Many observed destructive avalanches (code 6), but no in the DADB.
- Winter 1972/73: Good coincidence, but the fact that no avalanches are observed at all during the whole winter is not very realistic.
- Winter 1989/90: Good coincidence, but again no observed avalanches during the whole winter, except one in early May, which was reported three days later (see text).
- Winter 1991/92: Good coincidence. One skier accident is both in the DADB and reported by the observer.
- Winter 1992/93 and 1994/95: Bad coincidence. Accidents with snow cats in the ski area are recorded in the DADB, but not reported by the observer.

4.4. COMPARISON OF THE REGIONAL AVALANCHE ACTIVITY INDEX (RAAI) WITH THE DESTRUCTIVE AVALANCHES DATABASE (DADB)

Because the daily avalanche observations of individual stations are not very well correlated to analogous extracts of the DADB, whole regions are compared here. By averaging over whole regions a better agreement can be expected. In a first

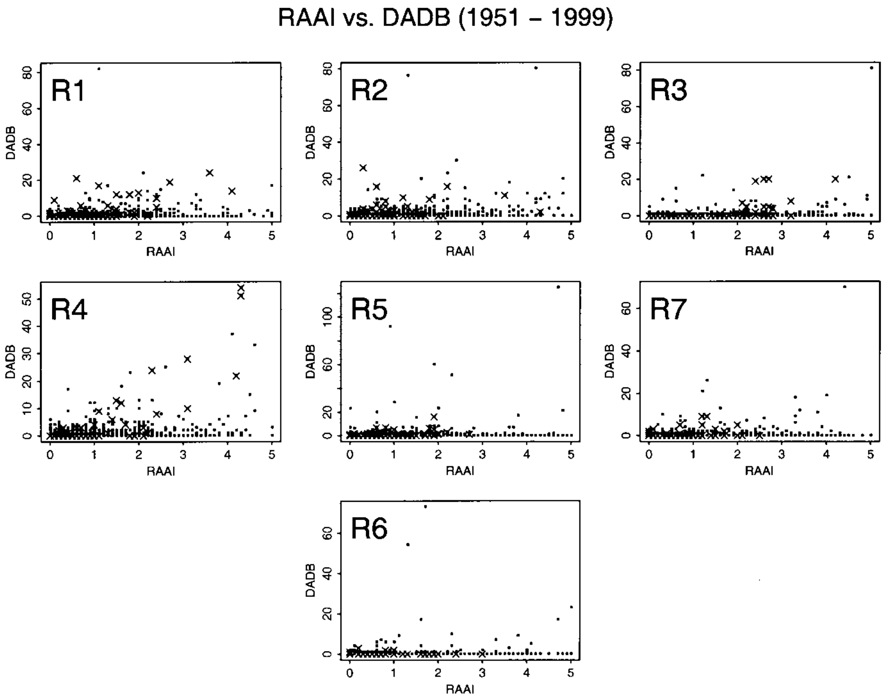

Figure 11. Regional Avalanche Activity Index (RAAI) versus total number of destructive avalanches from the DADB in daily resolution from 1951–1999 and for all seven regions R1–R7. Strictly speaking a certain day of the RAAI was compared with the previous day from the DADB. Values of the most recent winter 1998/99 are plotted as "x".

approach for every region the daily RAAI was plotted against the total number of destructive avalanches in this region from the DADB. Actually, because the avalanche observations are made in the morning and mainly report the avalanches from the day before, a certain day of the RAAI was compared with the previous day from the DADB. Figure 11 shows the daily values from the last 50 years. Based on the data classification days with small RAAI values will have no or hardly any destructive avalanches and from about RAAI > 3 the number of destructive avalanches should increase. However, no region shows this ideal performance, but it is best fulfilled in Region 4. Especially in the Regions 1, 2, 5 and 6 there are days with many destructive avalanches, but the corresponding RAAI was only around 1–2. This confirms the rather bad correlation between the two avalanche data archives, which has not improved in recent times ("x" in Figure 11 for the winter of 1998/99). By comparing the same days of RAAI and DADB, and not the previous day of the DADB, the correlation is even lower.

In a further analysis only severe avalanche periods with many destructive avalanches and/or high RAAI are compared. In such situations the agreement is expected to be best, because in situations with many destructive avalanches the RAAI should be high and vice versa. Figure 12 shows all situations with more

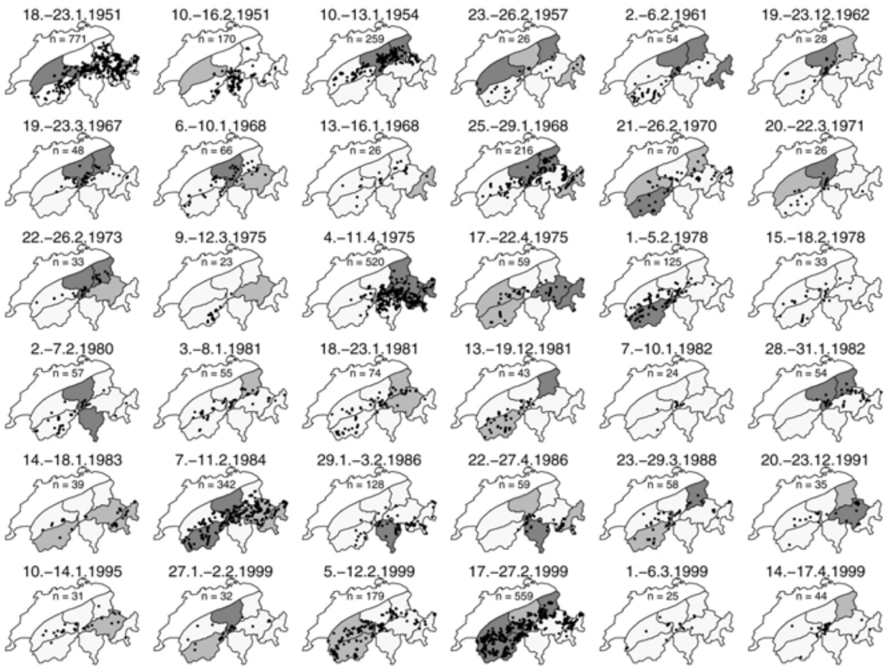

Figure 12. All situations with more than 20 destructive avalanches within two days (dots) from 1951–1999, overlaid by the highest RAAI during these periods for every region (grey areas). The three grey scales represent RAAI ≤ 3 (light grey), $3 <$ RAAI ≤ 4 (medium grey), RAAI > 4 (dark grey); white areas stand for "no observations". n is the total number of destructive avalanches.

than 20 destructive avalanches within two days from 1951–1999 together with the corresponding RAAI. In only a few cases the reported destructive avalanches are in all seven regions also well documented by the regional average of the avalanche observations (e.g., March 1967, March 1971, February 1973, January 1999). However, often the actual avalanche activity (DADB) is at least in some regions well reflected by the RAAI. For example in January 1954, many destructive avalanches occurred along the northern slope of the Alps, and the Regions 2 and 3 also attained a RAAI > 4. But the still strongly affected Region 1 got not over RAAI = 3, which is likely to attest unsatisfactory observations. Region 5 does not show a higher RAAI, because only the northern areas were touched by excessive avalanching and the majority of the observation stations could not have reported high avalanche activity. Finally there are also situations in which DADB and RAAI give a completely different impression of the avalanche activity (e.g., February 1957, February 1961, March 1975, December 1981, April 1999).

A slightly different approach is visualized in Figure 13, where all situations with RAAI > 4 for at least two successive days and in at least one region from 1951–1999 are shown together with the corresponding destructive avalanches. Most situations with "high" avalanche observations are not necessarily documented

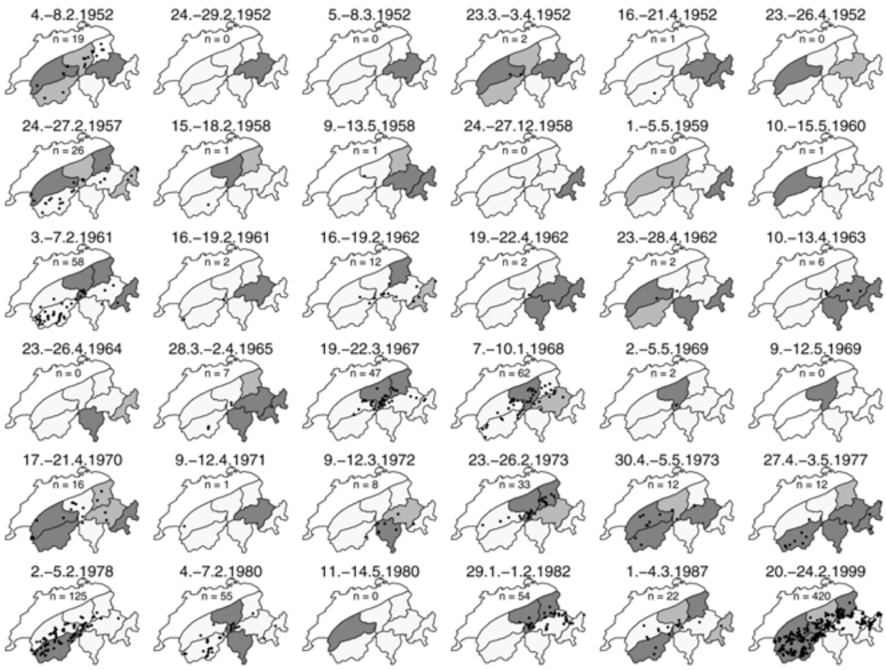

Figure 13. All situations with RAAI >4 for at least two successive days and in at least one region (grey areas) from 1951–1999, overlaid by the destructive avalanches (dots) during these periods. The three grey scales represent RAAI $\leq$ 3 (light grey), 3 $<$ RAAI $\leq$ 4 (medium grey), RAAI $>$ 4 (dark grey); white areas stand for "no observations". n is the total number of destructive avalanches.

by destructive avalanches in the DADB. For this situation, three explanations are possible: (i) by far not all situations with several big avalanches do actually cause destructions, what seems not very likely to us, (ii) the DADB is incomplete, what is not believed to be the case to this extent, or (iii) the avalanche observations are exaggerated. This last possibility seems most likely, particularly because all except one situations are before the L5-code change in winter 1987/88. The old code only distinguished between "small" and "big" avalanches, as already mentioned above, what makes it likely that "medium" avalanches were often reported as big avalanches, artificially increasing the RAAI.

5. Discussion and Conclusions

The daily avalanche observations of the SLF-observation station network bear a tremendous wealth of avalanche activity data for the last 50 years of up to 84 sites throughout the Swiss Alps. However, there are serious concerns regarding the data quality, what raises the question of the value and the usability of this data archive. The major goal of the avalanche observation programme is to obtain information about the avalanche activity for the operational avalanche warning and for the verification of the avalanche bulletin in retrospect. Since the avalanche bulletin by definition is a regional evaluation of the avalanche hazard, always a regionally averaged measure of the avalanche observations, such as the proposed RAAI, should be considered for any analyses. It does not seem justifiable to take only one selected station with approved reliable data for every region, because this single observation can seriously falsify the true picture of the situation in a whole region. However, as can be seen in Figures 12 and 13, situations with high observed avalanche activity do not coincide well with actually occurred destructive avalanches. From this it can be concluded that the avalanche observations in their present form are not a very reliable measure, and care should be taken by using them in avalanche forecasting models or for the retrospective bulletin verification. Further, as discussed in Section 4.2, the RAAI does hardly show significant long-term changes, and slight tendencies are always in doubt of being real or caused by the irregular data survey. This makes the avalanche observations difficult to use as an indicator for subtle changes of the avalanche activity. It is noteworthy, however, that the clear winter precipitation increase of up to 40% during the last hundred years found by Widmann and Schör (1997) is not reflected in the avalanche activity.

Regarding all these concerns, it can be debated whether the avalanche observations or the DADB represent the better avalanche activity data archive. It seems that the avalanche observations are best at a moderate level of avalanche activity and are decreasing both towards low and high avalanche activity. On the other hand, the DADB is particularly complete in severe avalanche winters, that means periods of high avalanche activity are best covered (Figure 14). However, consideration of only destructive avalanches can be problematic for various reasons: (i) Sometimes it is rather by chance that an avalanche causes a damage or not; it can stop a few metres above a railway line and then will not be recorded. (ii) During a period of more frequent avalanching the damage potential reduces over the years, because the antecedent avalanches may remove objects (buildings, forest), so that the subsequent avalanches can not cause destruction anymore. This was typical during the avalanche period in January 1954, when, after the extraordinary avalanches from January 1951 not much forest was left for destruction by the following avalanches a few years later. (iii) Constructional protective measures change the probability of an avalanche release and the run-out distance of avalanches. (iv) Whether a destructive avalanche occurs or not depends heavily on the actual land use, which can change dramatically with time.

For these reasons avalanche observations are a more objective measure of natural avalanche activity than only destructive avalanches, and avalanche observations will be for many years to come the only way to carry out an objective verification of the avalanche bulletin. Therefore a strong effort should be undertaken to significantly improve the consistency and reliability of these observations. There are two major problem areas to be solved: problems with the quality and continuity of the data, and problems with the data interpretation. The first point concerns the quality of the observations in the narrower sense (accurate obser-

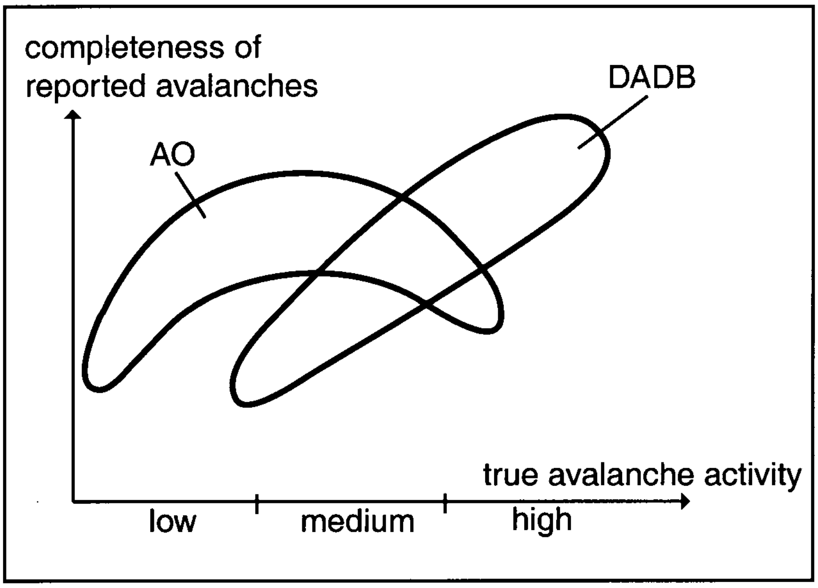

Figure 14. Completeness of avalanche observations (AO) and the destructive avalanches database (DADB) under various degrees of avalanche activity. The AO seem to reach a climax in medium avalanche activity, but then decrease again because of many missing values in situations of high avalanche activity. On the other hand the DADB gets more complete with increasing avalanche activity and occurrences of disastrous avalanche events. Isolated and small destructive avalanches in lean winters are often not reported. This demonstrates that both avalanche data archives have different ranges of "representativeness", which overlap.

vation guidelines, sufficient observer training, reliable observers, regular quality control) and an appropriate location of the observation station as well as shifts of the location and observer exchanges. The great variety of altitude and topography of the observation stations causes a natural "inhomogeneity" in the data population. High-elevated stations usually have a better overview and report more avalanches than low-lying stations, what leads to big differences within a very short distance. In fact, there exist several "station pairs" of mountain and valley sites, which are spatially close together, but because of their altitude difference show quite different observations (Bendolla – Grimentz, Egginer – Saas Fee, Weissfluhjoch – Davos, Motta Naluns – Ftan, Corvatsch – St. Moritz). This matter of fact certainly leads to a wide spectrum of possible conditions, but is not beneficial for a well-balanced, consistent regional average. In future, new stations should be erected at high-altitude sites whenever possible, such as ski areas or along maintained mountain pass roads, because the view into the surrounding avalanche terrain is much better and the people in charge of doing the observations (preferably ski and highway patrollers) are sensitized for this matter from their regular job.

To solve the second problem area concerning the data interpretation seems even more urgent. The mixed ordered-categoric scale of Avalanche Index L5 must be newly defined as a pure ordered intensity scale describing the magnitude of the natural avalanche activity. The impact and the avalanche activity must be separated and a new categoric code defined describing the impact only. Finally, new methods should be considered to get away from the subjective observation technique and to introduce automatic avalanche sensors. Beside quality concerns of man-made observations, it is no more acceptable to have no data in adverse weather, just because the low visibility prevents making any observations. Promising approaches based on acoustic (Adam *et al.*, 1998; Duclos *et al.*, 2001) and seismic techniques (Ammann, 1998; Suriñach *et al.*, 2001) are presently under development and no effort should be spared to operationally implement such systems.

Acknowledgements

This study would have been impossible without the great effort and dedication of innumerable observers doing their job during the winter season on a daily basis since many decades. Their constant commitment allows us today to draw conclusions out of a tremendous wealth of avalanche activity data. Further we would like to thank Sievi Gliott, Roland Meister and Thomas Stucki from the SLF Avalanche Warning Team for many fruitful discussions concerning the observation station network. Stephan Harvey, Urs Stöckli and Andreas Stoffel contributed as data providers. Further thanks are extended to Walter Ammann, Hans-Jürg Etter, Paul Föhn and Mark Schaer for commenting on earlier drafts of the manuscript, and to two anonymous reviewers for their suggestions improving the paper.

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