

Diss. ETH No. 14493

# **SNOW AND AVALANCHE CLIMATOLOGY OF SWITZERLAND**

A dissertation submitted to the  
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH

for the degree of  
DOCTOR OF NATURAL SCIENCES

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2002



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# Abstract

Throughout the European Alps snow is a resource of great commercial value (winter tourism, temporary reservoir for drinking water, irrigation and hydro-electricity). At the same time snow bears considerable hazards such as heavy loads on constructions, road closures and avalanches. Thus, adequate monitoring of snowfall and snow depth is an important social task. The two observational networks of the Swiss Meteorological Institute (SMA) and the Swiss Federal Institute for Snow and Avalanche Research (SLF) contribute since decades to an increasingly successful “snow management”.

The goal of this work is to examine the large amount of snow and avalanche data, which accumulated during the last half century from the operational SMA- and SLF-observer stations, to filter useful data and analyse the valuable long-term series. Additionally, the scientific basis is established for an extensive evaluation and reorganisation of the SLF observer station network. Three issues seem particularly important: 1) to preserve high-quality long-term stations for climate monitoring, 2) to maintain an evenly distributed number of stations divided into climatologically comprehensible regions and 3) to cooperate Alpine-wide allowing for cross-border data exchange.

For the first time nationwide long-term trends (1931 – 1999) of various snow parameters are presented. The results are of high relevance in the current climate change debate and well fit northern hemisphere snow trends found in the literature: a general increase — with interruptions — until the early 1980s followed by a statistically significant decrease towards the end of the century. Changes are amplified at low elevations. However, data processing clearly demonstrated that for monitoring subtle climatic changes, superimposed by large regional, altitudinal and annual variations, a sufficiently dense network of continuous snow stations resulting in homogeneous long-term series is necessary.

In order to determine the optimal station coverage, a probabilistic model based on the spatial extent and frequency of heavy snowfall events was developed. For local avalanche warning, for example, it is crucial to know whether or not we will miss small-scale heavy snowfall peaks in unmonitored country. Results show that ideal

networks should have a triangular spacing of about 15 km to obtain a spatially continuous snowfall capture probability of at least 80%. Spacings of 20 km result in only 50% guaranteed capture probability, which means at least half of all local snowfall peaks in areas of maximum distance between stations are missed and thus avalanche forecasts will locally underestimate the situation in at least half of all cases. Serious deficiencies in the Swiss operational snow observation network exist in the south/south-east and all along the national border, pointing up the necessity of cross-border data exchange.

Traditionally, the Swiss Alps are divided into seven snow-climatological regions, defined by major hydrological divides or district boundaries. However, spatial grouping of snow stations by cluster analysis revealed that these regions are only partially comprehensible from the climatological point of view and a new division is suggested. Good reasons for a change are manifold, since most applications dealing with the spatial interpolation of snow data revert to snow regions, be it for the calculation of regional altitude gradients or for the estimation of snow conditions for avalanche warning. Using inaccurate divisions obviously affects the result in a bad way. Differences between the new and old divisions are most obvious in the interior areas (Valais, Grisons), where the main snow-climate divide cuts right across some traditional regions.

Avalanche observations serve as an important basis for operational avalanche warning and are the main parameter to carry out an objective verification of the avalanche bulletin in retrospect. Thus, the determination of avalanche activity is a vital tool for successful risk management. However, it is very difficult to obtain objective and reliable avalanche data. A methodological approach to prepare and transform 50-year long series of inconsistent avalanche observations is shown, before temporal trend and spatial distribution of avalanche activity are discussed and compared with the Destructive Avalanches Database. Using different statistical descriptors, no change in avalanche activity could be detected, but a large year-to-year variability is typical. Finally, 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. Intensified research developing man- and weather-independent systems recording avalanche activity is urgently recommended.

# Kurzfassung

Im gesamten europäischen Alpenraum ist Schnee eine Ressource mit hoher Wertschöpfung (Wintertourismus, Speicher für Trinkwasser, Bewässerung und Wasserkraft). Zugleich birgt Schnee aber auch ein grosses Gefahrenpotenzial, zum Beispiel infolge hoher Schneelasten für Bauwerke, Strassenblockaden oder Lawinen. Deshalb ist die Überwachung von Neuschneefällen und der Gesamtschneehöhe eine bedeutende gesellschaftliche Aufgabe. Die beiden Beobachtungsnetze der Schweizerischen Meteorologischen Anstalt (SMA) und des Eidgenössischen Instituts für Schnee- und Lawinenforschung (SLF) tragen seit Jahrzehnten zu einer zunehmend erfolgreicherer "Schneebewirtschaftung" bei.

Ziel dieser Arbeit ist es, die grosse Menge an Schnee- und Lawinendaten, die während des letzten halben Jahrhunderts an den SMA- und SLF-Beobachterstationen anfiel, zu sichten, nutzbringende Daten herauszuziehen und wertvolle Langzeitreihen zu analysieren. Zudem wird die wissenschaftliche Grundlage für die Evaluation und Neuorganisation des SLF-Beobachternetzwerkes erarbeitet. Dazu scheinen drei Punkte besonders wichtig: 1) Qualitativ hochstehende Langzeitreihen zur Klimaüberwachung müssen unbedingt erhalten bleiben. 2) Stationen sollen gleichmässig verteilt und in klimatologisch begründbare Regionen eingeteilt sein. 3) Der grenzübergreifende Datenaustausch im gesamten Alpenraum muss gewährleistet sein.

Erstmals werden landesweite Langzeit-Trends (1931 – 1999) verschiedener Schneeparameter dargestellt. In der heutigen Klimaänderungsdebatte sind diese Resultate von grosser Bedeutung und stimmen gut mit nordhemisphärischen Schneetrends aus der Literatur überein: ein allgemeiner Anstieg — mit Unterbrechungen — bis in die frühen 80er Jahre, gefolgt von einem statistisch signifikanten Abfall gegen Ende des Jahrhunderts. In tiefen Lagen treten Änderungen verstärkt auf. Die Datenanalyse machte deutlich, dass zur Beobachtung von schleichenden Klimaveränderungen, die zudem noch von starken regionalen, höhenbedingten und jährlichen Schwankungen überlagert sind, ein genügend dichtes Netz von kontinuierlichen, langjährigen und homogenen Datenreihen notwendig ist.

Um die optimale Stationsdichte zu bestimmen wurde ein Wahrscheinlichkeitsmodell entwickelt, das auf der räumlichen Ausdehnung und der Häufigkeit von Starkschneefällen basiert. Für die lokale Lawinenwarnung zum Beispiel ist es entscheidend zu wissen, ob kleinräumige Starkschneefallspitzen im unbeobachteten Raum erkannt werden können oder nicht. Die Resultate zeigen, dass ideale Netzwerke eine Dreiecksmaschenweite von rund 15 km aufweisen sollten, um eine flächendeckende Schneefall-Erfassungswahrscheinlichkeit von 80% zu gewährleisten. Maschenweiten von 20 km garantieren nur eine 50%ige Erfassungswahrscheinlichkeit, was bedeutet, dass in Gebieten mit maximalem Abstand zwischen den Stationen rund die Hälfte aller kleinräumigen Schneefallspitzen übersehen werden und folglich die Lawinenvorhersage die Situation in wenigstens der Hälfte aller Fälle unterschätzen wird. Gravierende Defizite im schweizerischen operationellen Schneebeobachtungs-Netzwerk existieren insbesondere im Süden/Südosten und allgemein entlang der Grenze, was die Notwendigkeit von grenzüberschreitendem Datenaustausch verdeutlicht.

Traditionellerweise sind die Schweizer Alpen in sieben schneeklimatologische Regionen eingeteilt, die durch Hauptwasserscheiden oder Kantonsgrenzen definiert sind. Eine räumliche Klassierung von Schneestationen mittels Cluster-Analyse zeigt allerdings, dass diese Regionen nur teilweise klimatologisch begründbar sind. Deshalb wird eine neue Regionseinteilung vorgeschlagen, wofür es viele gute Gründe gibt. Die meisten Anwendungen, die auf der räumlichen Interpolation von Schneedaten basieren, greifen auf Schneeregionen zurück, sei es für die Berechnung von regionalen Höhengradienten oder für die Abschätzung der Schneeverhältnisse für die Lawinenwarnung. Dabei führt die Verwendung von unpräzisen Regionen offensichtlich zu Ungenauigkeiten im Resultat. Die Hauptunterschiede zwischen alter und neuer Regionseinteilung liegen vor allem in den inneralpinen Gebieten (Wallis, Graubünden), wo die Hauptschneeklimascheide quer durch die traditionellen Regionen verläuft.

Lawinenbeobachtungen liefern eine wichtige Grundlage für die operationelle Lawinenwarnung und sind der Hauptparameter für die objektive Verifikation des Lawinenbulletins im nachhinein. Deshalb ist die Bestimmung der Lawinenaktivität ein wesentliches Hilfsmittel für ein erfolgreiches Risikomanagement. Allerdings ist es sehr schwierig, objektive und zuverlässige Lawinendaten zu erhalten. Ein methodischer Ansatz wird aufgezeigt um 50jährige, uneinheitliche Lawinenbeobachtungsreihen aufzubereiten und zu transformieren, bevor die zeitliche und räumliche Verteilung der Lawinenaktivität diskutiert und mit der SLF-Schadenlawinendatenbank verglichen wird. Trotz Verwendung verschiedener statistischer Deskriptoren konnte keine grundsätzliche Veränderung der Lawinenaktivität festgestellt werden, allerdings sind

die jährlichen Schwankungen enorm. Schliesslich werden Empfehlungen zur Verbesserung des laufenden Lawinenbeobachtungsprogrammes abgegeben, um in Zukunft möglichst einheitlich erhobene und zuverlässige Daten zu erhalten. Insbesondere wird eine intensiverte Forschung empfohlen, um mensch- und witterungsunabhängige Systeme zur Erfassung der Lawinenaktivität zu entwickeln.



# Chapter 1

## Introduction

During the winter of 1936/37 the first snow mechanical experiments were carried out by a team of scientists of the newly founded Swiss Snow and Avalanche Research Commission on Weissfluhjoch above Davos. Simultaneously, regular snow and avalanche observations began at a research plot in the Parsenn ski area somewhat below Weissfluhjoch. With that the first snow stake of the 1942 founded Swiss Federal Institute for Snow and Avalanche Research (SLF) was established. After the war some of the observation stations maintained by the Swiss Army Avalanche Service were integrated into the newly set up SLF snow and avalanche observation network. However, it was not until after the severe avalanche winter of 1950/51 that a significant expansion of the station network took place. During the following years and decades the number of stations was constantly growing and by the year 2001 115 man-served SLF-stations were in operation.

The original purpose of the SLF observation stations was to provide necessary data for the elaboration of the national avalanche bulletin; climatological demands arose only later. In addition to the stations of the Swiss Meteorological Institute (SMA),<sup>1</sup> which are mainly situated at low levels and thus only to a small part useful for analyses related to snow and avalanche research, the SLF-stations are generally situated at high Alpine villages and ski resorts and the observation programme goes beyond purely meteorological parameters. Beside weather informations, new snow (HN) and snow depth (HS) measurements, on a daily basis a variety of other snow parameters are recorded and avalanche activity in the surrounding mountains is observed. Whereas data obtained from the research plot at Weissfluhjoch are extensively used for experimental purposes, data from further away stations were hardly ever analysed in retrospect, except HN and HS. These two parameters are also the only ones to be annually checked and erroneous values are corrected. Nationwide new snow and snow depth data from

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<sup>1</sup> new name: MeteoSwiss

SLF- and suitable SMA-stations were used on various occasions in the past, mainly related to climatological investigations (e.g., Witmer et al., 1986) and engineering purposes (e.g., SIA, 1989). Besides, HN- and HS-data are occasionally used for scientific case studies (e.g., SLF, 2000) or local expertises (dimensioning of avalanche retaining structures, court expertises after avalanche accidents, etc.).

The goal of this dissertation is to examine the large amount of data, which accumulated during the last 60 years from the operational SLF observer stations, to filter useful data, edit, process and analyse the valuable long-term data archive. Additionally, the scientific basis is established for an extensive evaluation and reorganization of the observer station network. Thus, the outcome is threefold: 1) To look through the voluminous data base and point out errors and inconsistencies; this has been done on an internal basis. 2) To aggregate quality-checked data and use the capacious data archive for climatological trend analyses; the results are presented in Chapter 2 and 5. 3) To reveal possible strategies for the network evaluation; two approaches are presented in Chapter 3 and 4 and the practical implementation will be done separately.

It was soon realized that the detailed examination of all available parameters would go far beyond the scope of a dissertation. Thus, it was decided to concentrate on three main parameters: Daily new snow, snow depth and avalanche observations. Quality-checked homogeneous snow series are relevant for various applications, such as for general snow-climatological purposes (mapping, trend analyses), avalanche warning (accurate real-time snow information), dimensioning of avalanche defence structures and hazard zoning (extreme value analysis), ski resort planning and operation (average expected snow coverage, touristic snow information), hydro-power management (optimal resources planning), etc. Beside SLF-data, also snow data from the Swiss Meteorological Institute and the Rhaetian Railway (RhB) were considered and analysed. Avalanche observations serve as an important basis for operational avalanche warning and are the main parameter to carry out an objective verification of the avalanche bulletin in retrospect. Thus, the determination of avalanche activity is a vital tool for successful risk management.

This work is divided into four main chapters containing the manuscripts of four papers prepared for publication in journals. Although they are thematically related and successively ordered, each chapter stands for itself and can be read separately:

**Chapter 2** highlights the significance of small-scale snow variability and station shifts for the homogeneity of long-term snow series and focuses on trend analyses of various snow parameters covering the last 70 years.

**Chapter 3** describes a probabilistic model based on the spatial extent and frequency of heavy snowfall events in order to evaluate how well heavy snowfalls can be captured by the various existing snow station networks and combinations of them.

**Chapter 4** demonstrates the spatial grouping of snow stations by clustering based on widely altitude independent HN-data and suggests the revision of the traditional seven snow regions into 10 – 14 new snow divisions.

**Chapter 5** shows a methodological approach to prepare and transform 50-year long series of inconsistent avalanche observations, before temporal trend and spatial distribution of avalanche activity are discussed and compared with the Destructive Avalanches Database.

Finally, Chapter 6 amalgamates the conclusions of all four previous chapters and provides an outlook for relevant further work. At the end all references are listed in a common bibliography.



## Chapter 2

# Climate Trends from Homogeneous Long-Term Snow Data

*Manuscript:*

*Latarnser, M. and Schneebeli, M.: Climate trends from homogeneous long-term snow data of the Swiss Alps (1931 – 1999). Submitted to International Journal of Climatology.*

### Abstract

The mean snow depth, the duration of continuous snow cover and the number of snowfall days in the Swiss Alps all show very similar trends during the observation period 1931 – 1999: a gradual increase until the early 1980s — with insignificant interruptions during the late 1950s and early 1970s — followed by a statistically significant decrease towards the end of the century. Regional and altitudinal variations are large; high altitudes show only slight changes and the trends become more pronounced at mid and low altitudes. The southern part of the Alps often has different conditions at a time than the north. Shorter snow duration is mainly caused by earlier snow melting in spring than by later first snowfalls in autumn.

Trends for heavy snowfall events are somewhat different: at elevations above 1300 m a.s.l. a very weak increasing trend persists towards heavier snowfalls since the 1960s and only low altitudes below 650 m a.s.l. show a marked drop since the early 1980s, indicating that heavy winter precipitation to an increasing degree falls in form of rain instead of snow.

A literature review confirms that throughout the temperate and subpolar northern hemisphere a similar general pattern of temporal snow variations occurred during the 20th century.

## 2.1 Introduction

Except for temperate mountainous and subpolar regions snow was for long time not an important factor of most human activities, because it is hardly ever present or only patchy during short spells in winter. Therefore, during the initialization period of many national meteorological services in the mid 19th century snow was a parameter of little significance and scarcely recorded. However, with the emergence of winter tourism and hydro-electric power production in Europe during the 1920s and 30s snow was recognized as a valuable resource and attracted the attention of businessmen, politicians and scientists. In consequence the meteorological services steadily increased their network with stations measuring daily new snow and total snow depth. This resulted in an increasing number of scientific articles about snow climatology in the Alps (e.g., Mörikofer, 1937; Eckel, 1938; Kuhnke, 1939; Prohaska, 1943; Mörikofer, 1948; Schalko, 1949; Zingg, 1954). Connected with a boom of ski resort development during the 1960s and 70s the availability and predictability of snow attained a vital interest for the European mountain regions. Costly national snow climate studies were tackled, such as Schüepp et al. (1980), Witmer (1986), Primault and Kummer (1992) in Switzerland or Fliri (1992) in Austria and climatological and hydrological atlases with sheets on various snow parameters were elaborated (SMA, 1987; LHG, 1992). A succession of three exceptionally warm and dry winters in the Alps from 1987/88 to 1989/90 led to widespread discussions about the economical consequences of snow shortage and the underlying reasons. It was argued that now the first clear signs of man-made climate change towards a warmer atmosphere were visible in the Alpine region (IPCC, 1990). Scenarios of future snow conditions were set up (Föhn, 1990) and their economical consequences for winter tourism (Abegg, 1996) and water management (Ehrler, 1998) studied. Long-term changes of various snow parameters for a few selected Alpine stations were already analysed by Ambühl (1961), Steinhauser (1970) and Brand (1991) and on the international scene during the 1990s publications on this topic multiplied (e.g., Beniston et al., 1994; Beniston, 1997; Bultot et al., 1994; Frei et al., 1999; Frei and Robinson, 1999; Hantel et al., 2000; Hartley and Keables, 1998; Hughes and Robinson, 1996; Jaagus, 1997; Leathers and Luff, 1997; Mohnl, 1991, 1993 and 1996; Serreze et al., 2001; Spreitzhofer, 1999; Ye, 2001).

However, homogeneous long-term snow records are not only necessary for climate modelling, but play an important role as reference data for annual runoff prognoses and daily avalanche forecasts. For this paper an effort was made to select a maximum number of homogeneous long-term snow series all over the Swiss Alps including the

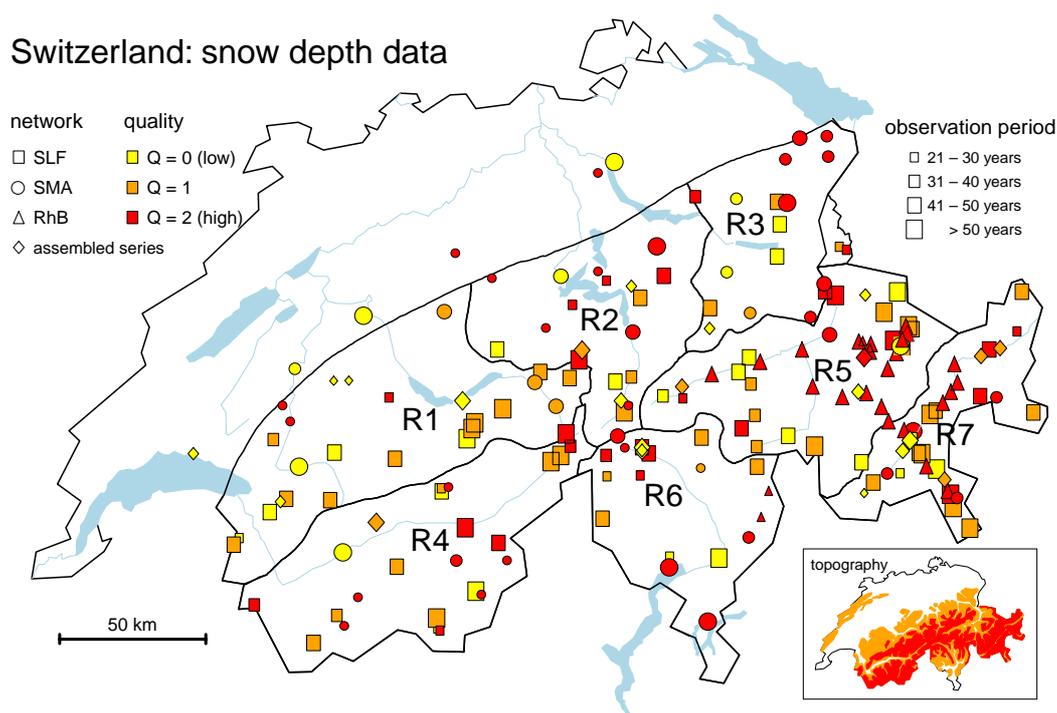
adjacent forelands. Problems connected with the small-scale variability of snow data and consequences for trend analyses are discussed. Then, trends of the average snow depth, the duration of snow cover, the number of snowfall days and heavy snowfall events are evaluated for a maximum period of 69 years (1931 – 1999). Finally, the results are discussed, put into an international frame and conclusions are drawn.

## 2.2 Data

In this study two main snow parameters are used: The total depth of snow cover (HS, in cm) and the depth of daily new snowfall (HN, in cm). HN and HS are measured every morning on a daily basis and HN for a given date represents the amount of new snow fallen since the previous morning. Winters are always named after the main part of the winter (e.g., 1999 means winter 1998/99).

The analyses are based on snow data from the dense observational networks of the Swiss Meteorological Institute (SMA) and the Swiss Federal Institute for Snow and Avalanche Research (SLF). For the canton of Grisons (South-east Switzerland) additional data from the Rhaetian Railway (RhB) were used (HS only). The area under investigation ranges over the entire Swiss Alps — divided into seven snow climatological regions (R1 – R7) — including the foothills and adjacent forelands in the north and south (Figure 2.1).

Although the conventional SMA climate network operates since 1864 and the first regular snow observations date back to 1892 (Maurer et al., 1909), the earliest officially digitalized snow data are not available before 1931. Most early climate stations were set up in low lying areas with not much snow and at the few mountain stations snow was either not measured or the observations were very patchy. Exemptions are Davos (1560 m a.s.l.) and Bever (1710 m a.s.l.), for which Schneebeli et al. (1998) digitalized the original observation diaries as far back as possible (Davos: HS since 1893, HN since 1900; Bever: HN and HS since 1902). However, the observations in Bever were given up in 1983 and the location of the observation station in Davos was shifted several times, with a major shift of three kilometres in 1977. The ready availability of usable snow data, station shifts and closures of long-term sites are a severe problem for snow trend studies and we end up having only one mountain station in the northern foothills (Einsiedeln, 910 m a.s.l.) with continuous and homogeneous records from 1931 through to today.



*Figure 2.1:* Map of Switzerland with the spatial distribution of all 190 HS-stations with more than 20 years data including information of the network, data quality (see text) and length of observation period. R1 – R7 refer to the seven main snow-climatological regions of the Swiss Alps. The inset shows the topography (white: < 1000 m, light grey: 1000 – 2000 m, dark grey: > 2000 m).

The situation improved much with the buildup of the SLF network (SLF, 1948 and following years). After the initial station at Weissfluhjoch (since 1937) some more stations were added in the 1940s and a large expansion took place in the 1950s. Whereas continually more new stations opened, some old ones closed. By the year 2001 115 man-served SLF-stations were in operation. Whereas SMA-stations are mainly situated in the flatlands and the foothills (inter-quartile altitude range 480 – 1330 m a.s.l.),<sup>2</sup> SLF-stations focus on high Alpine villages and ski resorts (inter-quartile altitude range 1300 – 1760 m a.s.l.). However, it was not before the 1990s that automatic stations were introduced measuring the snow depth at high Alpine sites (SMA, 1995; Lehning et al., 1998). Beside ten automatic ENET-mountain stations, in the winter of 2000/01 the rapidly increasing network of automatic IMIS-stations encompassed 76 snow stations with an inter-quartile altitude range of 2110 – 2520 m a.s.l. Because of the short data series neither ENET- nor IMIS-stations were considered for this study. Nevertheless, the automatic network bears a tremendous wealth of snow depth (and other) data for future trend analyses in the high Alpine region.

<sup>2</sup> Based on all stations of the SMA-Climate Database; only a part of them (mainly in higher areas) was used in this study.

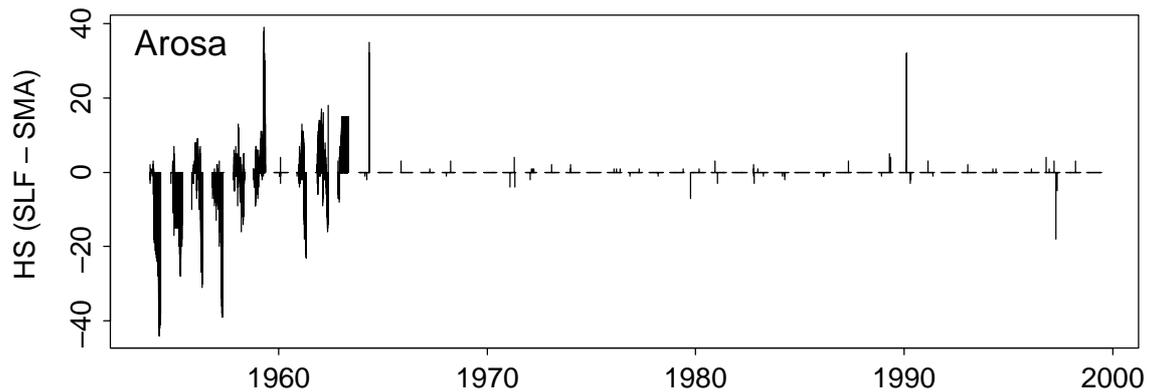


Figure 2.2: HS-difference between daily SLF- and SMA-data from Arosa. Before 1963 the two stations used to be at different locations, afterwards both stations were pooled together.

A very valuable addition to both SMA and SLF snow data are the daily HS-measurements available from up to 50 railway stations along the extensive network of the Rhaetian Railway (RhB). Data series start in 1954 or 1955 and mostly continue till the mid 1990s. Since many RhB-stations lie in areas with no other close-by snow stations, the data of 33 RhB-stations were digitalized for this study. These data allow for highly resolved distance (5 – 10 km) and altitude (100 – 300 m) profiles.

For locations with two parallel data series from different networks the longer and more complete series with as few station shifts as possible was taken. Occasionally two data series with overlapping time ranges were assembled and obvious errors corrected. For example, in *Arosa* (1820 m a.s.l.) HS-data from the SMA-network are available since 1950 and HN-data even since 1931; the station remained always at the same location. In 1954 an SLF-station opened in Arosa, however, initially it was at some distance and 78 m vertical away from the SMA-station causing HS-differences of up to 40 cm (Figure 2.2). In 1963 the SLF-station was shifted to the SMA-site and the two stations were pooled together resulting in almost identical data series. Deviations after 1963 can be the result of printing mistakes feeding the two different databases and the SLF-data being quality-checked and erroneous values corrected. For the long-term homogeneity the SMA-series are certainly better, but because the SLF-data are quality-checked, they are preferred after 1963. However, until 1972 the SLF-data have in the beginning and towards the end of winter often missing values (the snow was measured daily, but only fed into the SMA-database!), what finally led to the decision that the Arosa series was put together from the SMA-series (1931 – 1972) and the SLF-series (1973 – 1999).

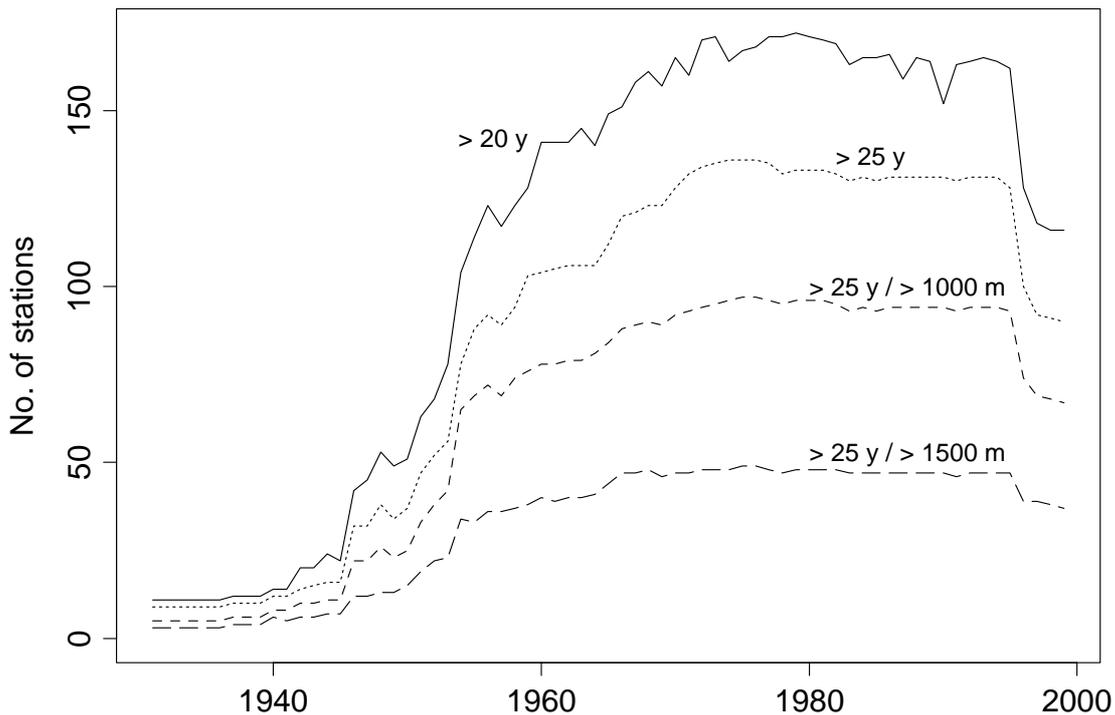


Figure 2.3: Temporal development of the availability of HS-data. The uppermost (solid) line reflects all stations  $> 20$  years data. The second (dotted) line shows only homogeneous stations with  $> 25$  years data, which are finally used for long-term trend evaluations (see text, Section 2.4). The two lower (dashed) lines indicate homogeneous stations  $> 25$  years data on altitudes above 1000 and 1500 m a.s.l., respectively.

Altogether for this study 190 HS-stations with more than 20 years of data (94 SLF, 48 SMA, 26 RhB, 22 assembled series) and 163 HN-stations (93 SLF, 54 SMA, 16 assembled series) were considered. The spatial distribution of the HS-stations is shown in Figure 2.1. Additional information for each station includes the network, the length of the observation period and a *quality index*  $Q$  concerning the long-term homogeneity.  $Q$  depends on possible station shifts during the entire observation period and takes values from 0 (at least one major station shift  $> 50$  m vertical or  $> 500$  m horizontal), 1 (one or several minor shifts) and 2 (never any shifts). Density and quality of long-term stations are increasing from west to east. One reason for that is the incorporation of RhB-data. Figure 2.3 visualizes the temporal development of the availability of HS-data. During the 1930s and 40s the station coverage was rather meagre, the sharpest rise took place during the 1950s. High-altitude stations are particularly few in the early years but by 1965 they have reached a near constant level. Due to SMA- and RhB-network cutbacks the number of stations drops again at all elevations since 1995. The spatial distribution for different altitude ranges is displayed in Figure 2.4. Most striking is the non-availability of homogeneous, long-term high-altitude stations ( $> 1900$  m) in

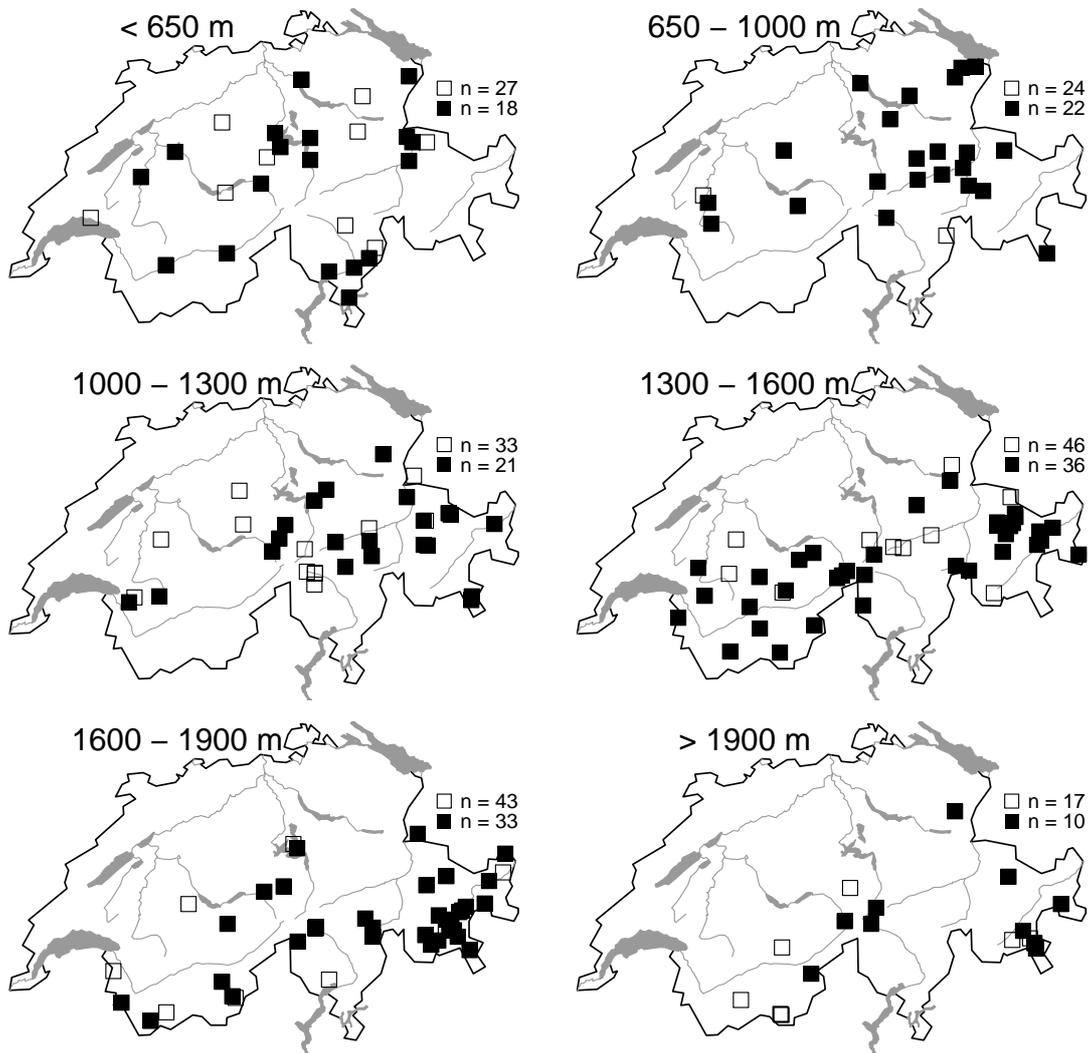


Figure 2.4: Spatial distribution of HS-stations for different altitude ranges. Empty (white) squares indicate all stations > 20 years data, filled (black) squares show only homogeneous stations with > 25 years data during the time period 1931 – 1999.

the west, south and central east and the missing mid-altitude range (650 – 1300 m) in the south and southwest. In some parts (especially in the southeast) there are hardly any low-lying stations, but this is natural because the altitude hardly drops below 1000 m a.s.l. in these places. On the other hand, there is a strong cumulation of mid-to-high-altitude stations (1300 – 1900 m) in the east and southeast. Averaged over whole Switzerland, from the 1950s onwards the altitudinal distribution is evenly spread and thus the dataset can be regarded as continuous through time.

## 2.3 Small-scale snow variability and consequences for trend analyses

For trend analyses with subtle changes the quality and homogeneity of the data series is of decisive significance. We demonstrate on a few examples how sensitive station shifts over short distances can influence the result of long-term trends.

### 2.3.1 Apparent climate trend of long-term snow data due to station shifts

*Davos* (1560 m a.s.l.) is one of the very few Alpine stations of Switzerland with more than 100 years of digitalized HS-data (Schneebeili et al., 1998, p. 24) and therefore is extremely valuable for long-term climate change analyses. From about 1900 – 1920 the mean seasonal snow depth (Nov – Apr) was generally above average, then turned to below average for the next two decades before remaining rather constant for the following 40 years (Figure 2.5a). Since about 1980 there seems to be a clear downward trend, which has been interpreted as a climatological signal (Beniston et al., 1994; Beniston, 1997). However, this trend is mainly the result of the relocation of the meteorological station in 1977 to another place three kilometres away. Since 1946 the 107 years long SMA series can be compared with the series of the nearby SLF station (Figure 2.5b). The difference between both series (SLF – SMA) evinces an obvious and systematic break in 1977. Before this date the mean difference of the seasonal snow depth was distinctively negative ( $-7.7$  cm), but after 1977 the mean difference was mainly positive ( $+6.1$  cm) resulting in a difference change of  $\Delta d = 13.8$  cm or about 25% of the mean seasonal snow depth (Figure 2.5c). In 1977 the SMA station was moved from Davos Platz about three kilometres to Davos Dorf and lies now within 250 m of the SLF station, always remaining at about the same altitude. Also the SLF station had a shift of 500 m in 1981 and since then has been slightly moved several times within 50 m. However, the SLF series show no significant trend during the last 54 years and the 1977 – 1999 period is only slightly higher ( $+5.4$  cm) than the 1946 – 1976 period. In contrast to that the SMA station shows a drop of  $-8.4$  cm between 1946 – 1976 and 1977 – 1999. By correcting the last 23 years of the SMA series with  $\Delta d = +13.8$  cm a “homogenized” series can be produced, which shows only a weak decline in recent times (Figure 2.5a, dashed line).

Splitting the entire winter season into three part seasons (early winter, mid winter, late winter) reveals a very similar behaviour (Figure 2.6). However, in early winter the difference between the two stations is least pronounced ( $+3.7$  cm) and in late winter

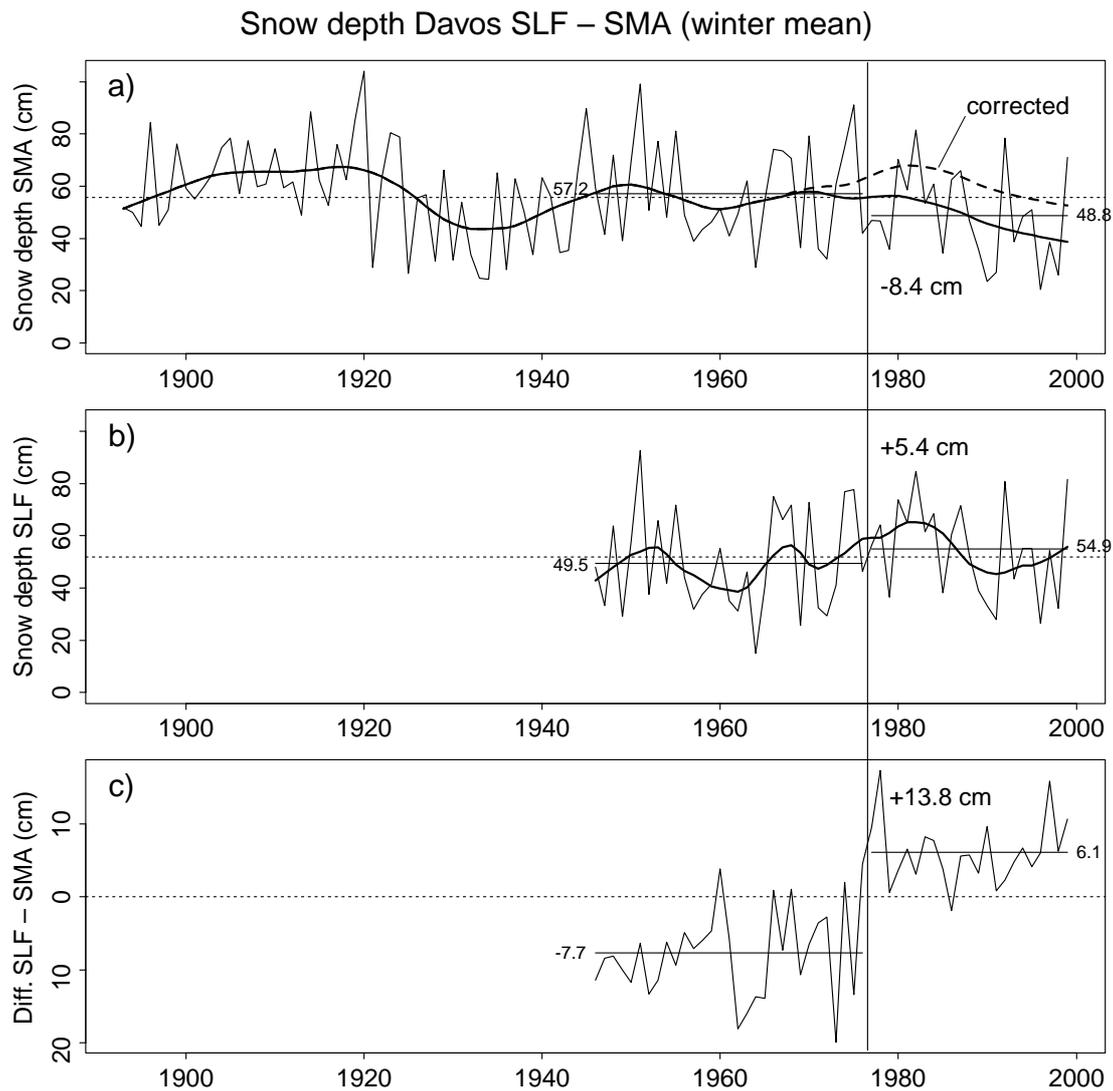
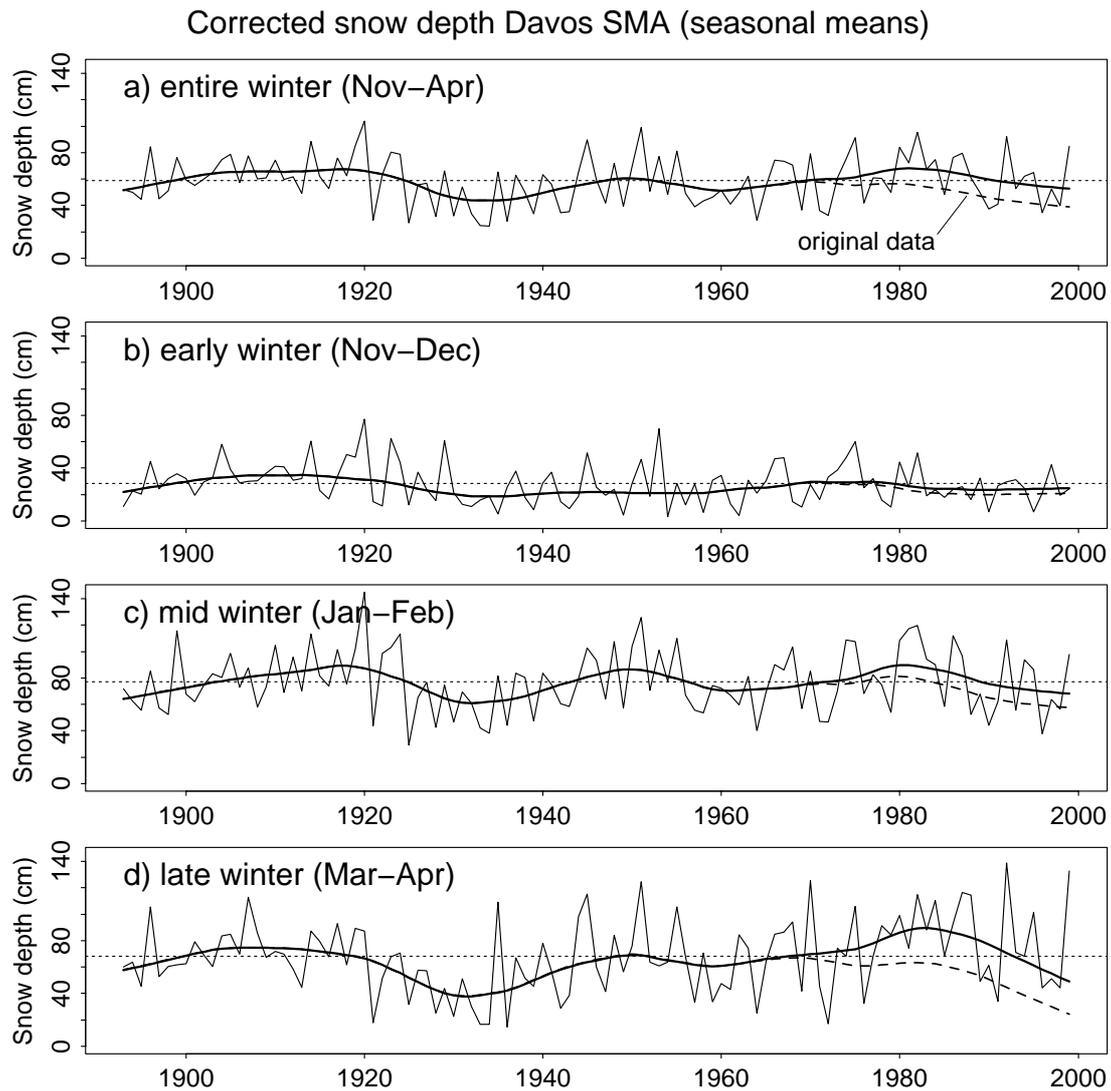


Figure 2.5: Mean seasonal snow depth from November to April for (a) Davos SMA (1893 – 1999) and (b) Davos SLF (1946 – 1999) including lowess-smoother ( $f = 0.2$ ) and overall mean (dotted line). The difference of both series during the common years of data (c) shows a systematic break in 1977, caused by the relocation of the SMA-station. The dashed curve on the right wing in (a) shows the smoothed line of the corrected values (+13.8 cm) for Davos SMA.

most pronounced (+27.1 cm). This stands in coincidence with the fact that inter-annual variations grow larger from early to late winter, but in recent times do not exceed previous long-term variations. Around 1980 early winters rather tend to have less snow than usual, whereas in late winter the snow depth is clearly above average.

Earlier shifts of the SMA station in 1900, 1930 and in 1962 may have also influenced the homogeneity of the long-term series. But all these shifts were within short distances and between comparable locations and therefore seem not to be of great significance.



*Figure 2.6:* Corrected mean seasonal snow depth of Davos SMA from 1893 – 1999 for (a) the entire winter season, (b) early winter, (c) mid winter and (d) late winter including lowess-smoother ( $f = 0.2$ ) and overall mean (dotted line). Before 1977 the original series are drawn, afterwards the annual values are corrected according to the difference to the reference station Davos SLF. The dashed curve on the right wing shows the clear downward trend of the uncorrected original data.

This demonstrates that we have no possibility to detect eventual systematic inhomogeneities in retrospect without having a neighbouring station in very close vicinity (order of magnitude 100 m). Additionally — and very important — station shifts can normally not be recognized when using the data from electronic databases, unless they contain a separate file with an up-to-date station history. However, this is often not the case (or only incomplete) and much effort must be undertaken to thoroughly compile the station history from archive documents.

### 2.3.2 Assessing the small-scale variability of snow data by comparing neighbouring stations

The amount of new snow, and due to the cumulative effect even more the snow depth, can vary considerably over short distances. This is demonstrated by comparing “station pairs”, stations in the same village, but from two different observation programmes and being in the order of magnitude of hundreds of metres apart from each other. The SLF station in *Andermatt* (1440 m a.s.l.) started records in 1941, was several times slightly shifted within 50 – 100 m in its first years, but then remained on its present location since 1954. The SMA station in *Andermatt* exists since 1864, but snow data are either non-existent or very scarce until the 1940s and electronically not available before 1967 (Schneebeil et al., 1998, p. 22-23). The SMA station was never moved since 1967 and is located 180 m from the SLF station in a very similar setting and at the same altitude. The “undisturbed” history of both stations is well reflected in the constant difference plot over the common 33 years of observation (Figure 2.7). The daily HN-differences do rarely exceed 10 cm and a few outliers of up to 30 cm difference can be regarded as being typing errors in the SMA data.<sup>3</sup> While slight HN-differences between SLF and SMA are common (74% of all days with snow fall have differences  $\geq 1$  cm), large deviations are rather exceptional (7% with differences  $> 5$  cm) and the mean difference of all snow fall days is only 1.9 cm. For HS the picture looks similar but generally the differences between the two stations are larger. The mean difference is 8.0 cm, 25% of all days have differences  $> 10$  cm and towards spring the differences get largest with up to 60 cm. Making this analysis for 13 station pairs distributed throughout the Swiss Alps reveals that even within a few hundred metres and on similar settings the small-scale variability averaged during the whole winter is in the order of 2.5 cm for HN and 10 cm for HS. 5% of all days (95%-quantile) have HS-differences  $> 28$  cm and 1% (99%-quantile) even  $> 41$  cm (Table 2.1). This finding is decisive for extreme value analysis, which — among other purposes — is the basis for avalanche dynamics calculations, hazard zoning and the dimensioning of avalanche defence constructions.

*Oberiberg* (1090 m a.s.l.) is another location with an SLF- and SMA-station pair (Figure 2.8). According to the station history the two stations were never moved and are situated 180 m apart from each other with 13 m altitude difference. However, the HS-difference plot displays obvious systematic breaks in 1978 and 1985. Before 1978 the SLF station usually had more snow (mean = +10.4 cm) and afterwards until 1984

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<sup>3</sup> Whereas all SLF snow data were manually quality-checked, the SMA data underwent only an automated plausibility test.

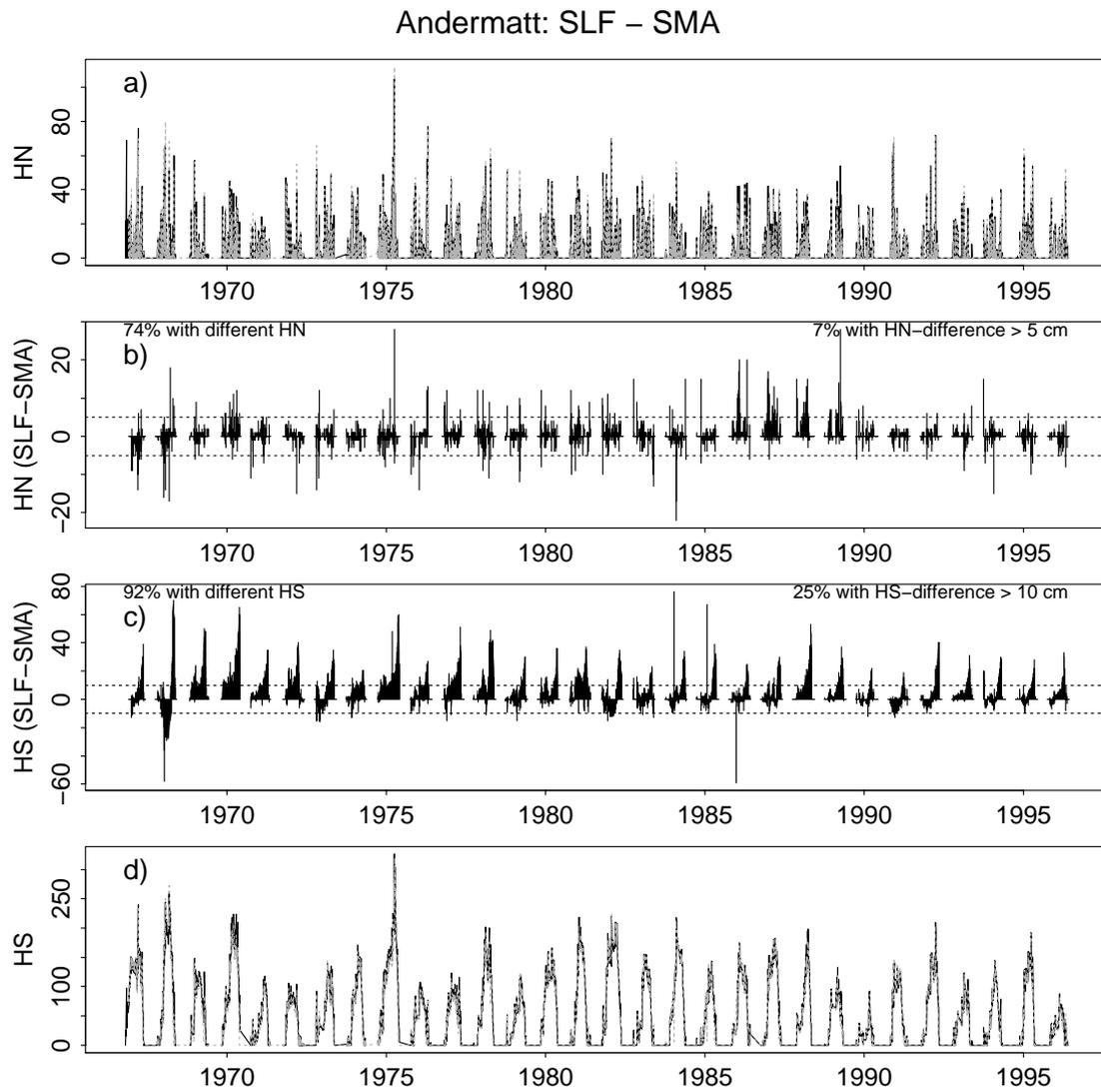


Figure 2.7: Comparison of daily SLF- and SMA-snow data from Andermatt. (a) shows the superimposed HN-data from SLF (solid line) and SMA (dotted line); (d) is the same for HS. (b) shows the HN- and (c) the HS-difference between SLF and SMA. The dotted lines indicate the  $\pm 5$  cm difference interval for HN and the  $\pm 10$  cm interval for HS. Neither difference plots nor absolute data series reveal obvious irregularities.

Table 2.1: Small-scale HS-variability within a few hundred metres distance over level terrain. Minimum-, median- and maximum-distribution of the 50%-quantile (median), 75%-, 95%- and 99%-quantiles of HS-differences of 13 station pairs. The 99%-quantile was taken instead of the 100%-quantile (maximum) in order to avoid outliers.

	<i>Minimum</i>	<i>Median</i>	<i>Maximum</i>
50%-quantile	2 cm	7 cm	11 cm
75%-quantile	4 cm	14 cm	21 cm
95%-quantile	11 cm	28 cm	52 cm
99%-quantile	23 cm	41 cm	98 cm

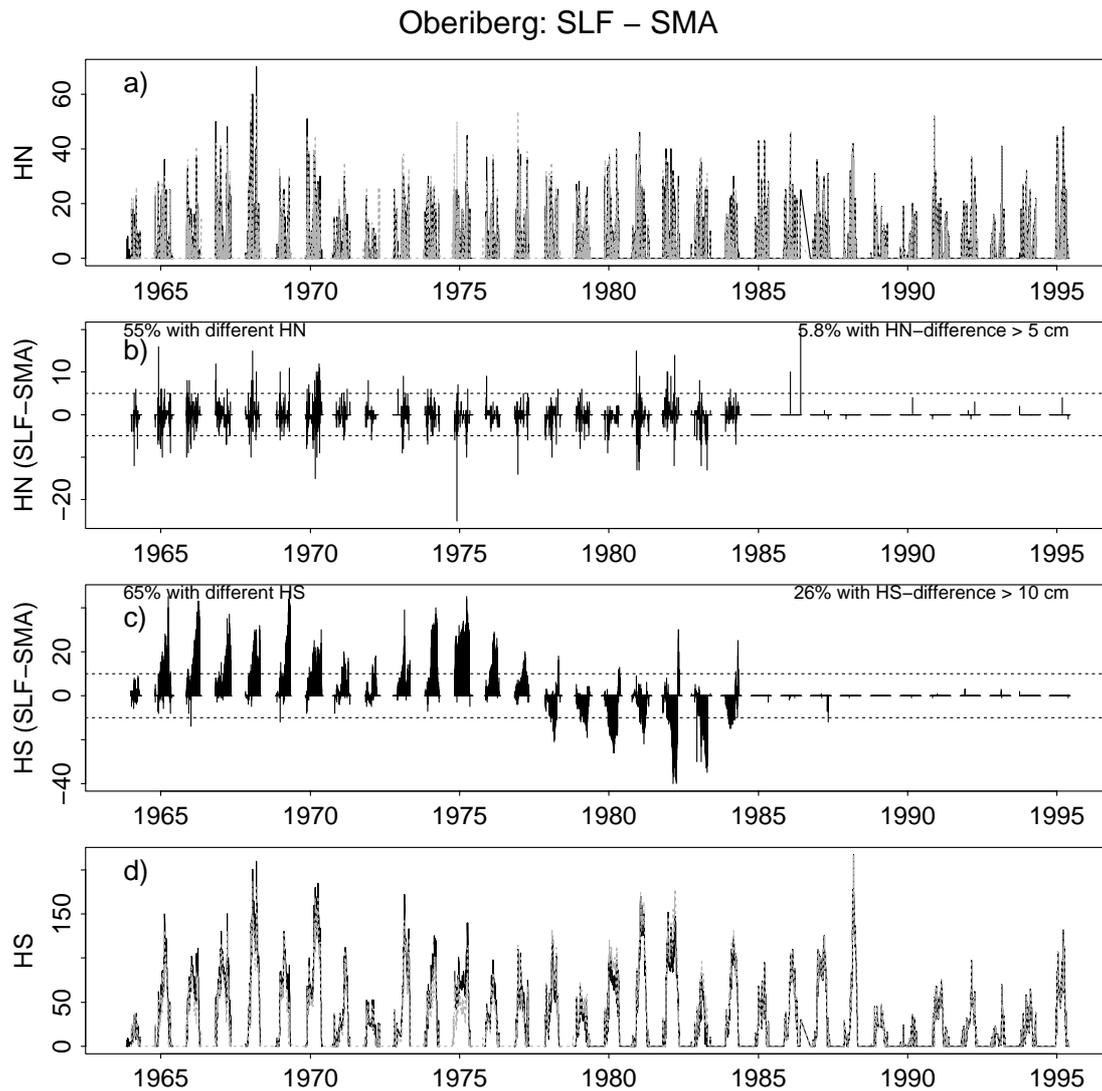


Figure 2.8: The same as Figure 2.7, but for Oberiberg. The minor station shift in 1978 can only be recognized in the HS-difference plot (c).

noticeably less (mean =  $-7.3$  cm) than the SMA station. This finding assumes that, although not documented, at least one station must have been shifted in 1978 or the close surroundings must have been altered drastically, for example, by the construction of buildings, what led to a significantly different snow accumulation pattern (changed windfield and/or sunshine duration). And later on, in 1985, one station must have been given up and pooled together with the other; otherwise the practically identical data series can not be explained. A checking call to the observer on duty verified the assumption (A. Holdener, pers. comm., May 2001): in 1978 the SMA-station was moved by about 50 metres, because a new house was constructed very close to the ancient observation plot, and in 1985 the previous SLF-station was given up and pooled

together with the SMA-station. Obviously such small-scale station shifts can have big effects on the absolute snow depth, which can not be detected by looking at the actual time series itself (Figure 2.8d). Only the comparison with directly neighbouring stations in the order of magnitude of hundreds of metres apart can give us a certain guarantee to detect systematic breaks and inhomogeneities. Thereby HS is a much better parameter than HN, where usually no irregularities can be seen (Figure 2.8b, 1964 – 1984). This example demonstrates that utmost care must be taken by using any long-term snow data series for subtle trend analyses, the station history must be carefully studied and even then the results should be treated with sound scepticism. Most often we are not in the lucky situation having close-by station-pairs for comparison.

## 2.4 Long-term snow trend analyses

### 2.4.1 Data parameters and method

For all further trend analyses only homogeneous long-term stations within the period of 1931 – 1999 were considered. “Homogeneous” in our sense means that the location of the observation site was never or only slightly shifted during the entire period of observation ( $Q = 1$  or  $2$  in Figure 2.1); “long-term” means that the station has at least 25 years of observation. For some stations with long-term records but a major homogeneity break, only parts ( $\geq 25$  years) of the entire series before or after the break were taken (e.g., Davos SMA 1931 – 1976). That results in a total of 140 HS-stations and 120 HN-stations.

First, the **mean seasonal snow depth** from 1 November to 30 April is analysed. Apart from the whole winter also two-monthly part seasons and the economically important Christmas – New Year period are investigated. The year-to-year variability and decade averages are spatially visualized and regional time series are shown and tested for significant trends.

Second, **duration** ( $d_0$ ), **beginning** ( $b_0$ ) and **final dates** ( $e_0$ ) **of the snow cover** are examined. Only the time period during which the ground was continuously covered with snow ( $HS > 0$  cm) is considered. If after a first snowfall in autumn or early winter all snow melts again, only the next snowfall date, when afterwards the snow remains on the ground for the rest of the winter, is taken as the beginning date. The corresponding condition applies for the final date in spring. Thus, the duration of snow cover is the number of days between  $b_0$  and  $e_0$  and equals the longest period with a continuous

snow cover. Since our data set covers only the eight-month winter period from 1 October to 31 May, these two dates are the utmost possible boundaries for  $b_0$  and  $e_0$ , but may be exceeded in reality in some years at high-situated stations. The values for  $b_0$  and  $e_0$  are counted days starting from 1 October. Thus, the earliest possible beginning date is 1 and the latest possible final date and maximum duration is 243 (244 in leap years). Particularly at low-lying stations, which usually do not have a continuous snow cover during the whole winter,  $b_0$  and  $e_0$  may strongly fluctuate from year to year. One winter the longest period with a continuous snow cover may be in December and an other year it may be in February and thus, although  $d_0$  may be similar,  $e_0$  in one winter may be before  $b_0$  in an other. Apart from  $HS > 0$  cm, duration, beginning and final dates are also determined for other **HS-thresholds > 20, 30, 50 and 70 cm** ( $d_{20} - d_{70}$ ,  $b_{20} - b_{70}$ ,  $e_{20} - e_{70}$ ). Already Eckel (1938) suggested several thresholds as a basis for the evaluation of ski resorts with regard to their suitability for alpine skiing and considered 30 cm as sufficient, 50 cm as good and  $> 70$  cm as excellent for skiing. In this context the **snow depth reached in the minimum during 100 days** ( $hs_{100d}$ ) is of particular interest, since investigations on ski resort development are only economically profitable if during at least 100 days enough snow is on the ground for the installations to be used (“100-days-rule”: Witmer, 1986; Abegg, 1996). The critical lower  $hs_{100d}$ -limit depends on the roughness of the terrain and averages about 20 – 30 cm on 1500 m resort altitude (Föhn, 1990).

For the evaluation of the parameters related with snow cover duration missing values (NA) must be treated with particular care. Especially in early records frequent missing values exist in the beginning and at the end of the observation period and often records started with the first significant snowfall and ended on the last day with snow on the ground. However, sometimes records start after the actual beginning date and end before the true final date. In this case, the values for  $b_0 - b_{70}$ ,  $e_0 - e_{70}$  and  $d_0 - d_{70}$  can not be correctly determined and must be left missing. The following conditions are used to decide whether beginning and final dates, and consequently also the duration of snow cover, are distorted by missing values (examples for HS-threshold  $> 0$ ):

$$\text{if } (HS_{b_0-1} = \text{NA} \ \& \ HS_{b_0} \neq HN_{b_0}) \quad \left\{ \begin{array}{l} \rightarrow b_0 = \text{NA} \\ \rightarrow d_0 = \text{NA} \end{array} \right. \quad (2.1)$$

$$\text{if } (HS_{e_0+1} = \text{NA} \ \& \ HS_{e_0} > 10) \quad \left\{ \begin{array}{l} \rightarrow e_0 = \text{NA} \\ \rightarrow d_0 = \text{NA} \end{array} \right. \quad (2.2)$$

For other HS-thresholds the above rules apply accordingly. Superior to that all parameters will be NA, if more than 125 days ( $\approx 4$  months) have missing values. If two or more snow periods within one winter have the same length, only the first period is taken. For hs100d an other rule is used to decide whether missing values distort the result or not. Initially, all data including missing values are taken to calculate a provisional  $hs100d_{prov.}$  (the 100th rank of the ordered HS-series). However, this may be too low for stations with many missing values within the 100-day-period. On the other hand, it does not matter if missing values exist beyond the  $hs100d_{prov.}$ -limit. To decide whether  $hs100d_{prov.}$  is plausible or not, the value of the duration of snow cover of the next lower HS-threshold is regarded. For example, if  $hs100d_{prov.} = 56$  cm, the next lower HS-threshold for the snow cover duration is 50 cm (possible HS-thresholds are 0, 20, 30, 50 and 70 cm) and thus d50 is taken for decision:

$$\text{if ( d50 = NA | d50 = 0 )} \quad \rightarrow \quad hs100d = NA \quad (2.3a)$$

$$\text{else if ( d50 > 0 )} \quad \rightarrow \quad hs100d = hs100d_{prov.} = 56 \quad (2.3b)$$

This means (2.3a), if the duration of snow cover exceeding 50 cm could not be determined ( $d50 = NA$ ) or equals zero, it is likely that  $hs100d$  can not exceed 50 cm and therefore  $hs100d_{prov.}$  is distorted by too many missing values. In case (2.3b) most often  $d50$  will be  $\geq 100$ , but also values of  $d50 < 100$  are possible; however they must certainly be  $> 0$ . Low-lying stations may not even have 100 days with any snow and  $hs100d$  will be zero.

After these various snow depth parameters, trends on **daily new snowfall** are analysed for long-term changes. The seasonal sum of daily HN correlates to 88% with the mean seasonal snow depth and thus shows very similar trends as the HS-mean. Therefore the HN sum is not further discussed here. But the **number of days with snowfall** above several HN-thresholds is investigated. The selected **thresholds** are **HN > 0, 10, 20 and 50 cm** of daily new snowfall. Additionally, the **annual maximum new snow sum of three successive days** (HN3max, the value for a given date means the HN-sum of the three precedent days) is taken as an indicator for heavy snowfall events and is often connected to periods with spontaneous climax avalanches.

Because absolute snow data contain big scatter due to highly variable topography, trend analyses are made for the relative deviation from the long-term mean. To benefit from the maximum possible data range (within 1931 – 1999), the long-term mean is calculated for every station individually according to its entire observation period and

thus is based on different periods for different stations. All calculations are performed with S-Plus (StatSci, 1993). The maps shown in Figures 2.9 – 2.13 and 2.25 are based upon linear interpolation within a triangulation scheme (S-Plus functions *interp* and *image*) and the *lowess*-smoother used in Figures 2.5 – 2.6, 2.14 – 2.24 and 2.26 applies a robust locally linear fit to scatterplot data. The fraction  $f$  of the data used for smoothing at each point determines the window inside which points are weighted so that nearby points get the most weight. The larger  $f$ , the smoother the fit. For all long-term trends the default value  $f = 0.67$  was taken except for Figures 2.5 – 2.6, where  $f = 0.2$  was applied in order to see short-term variations better.

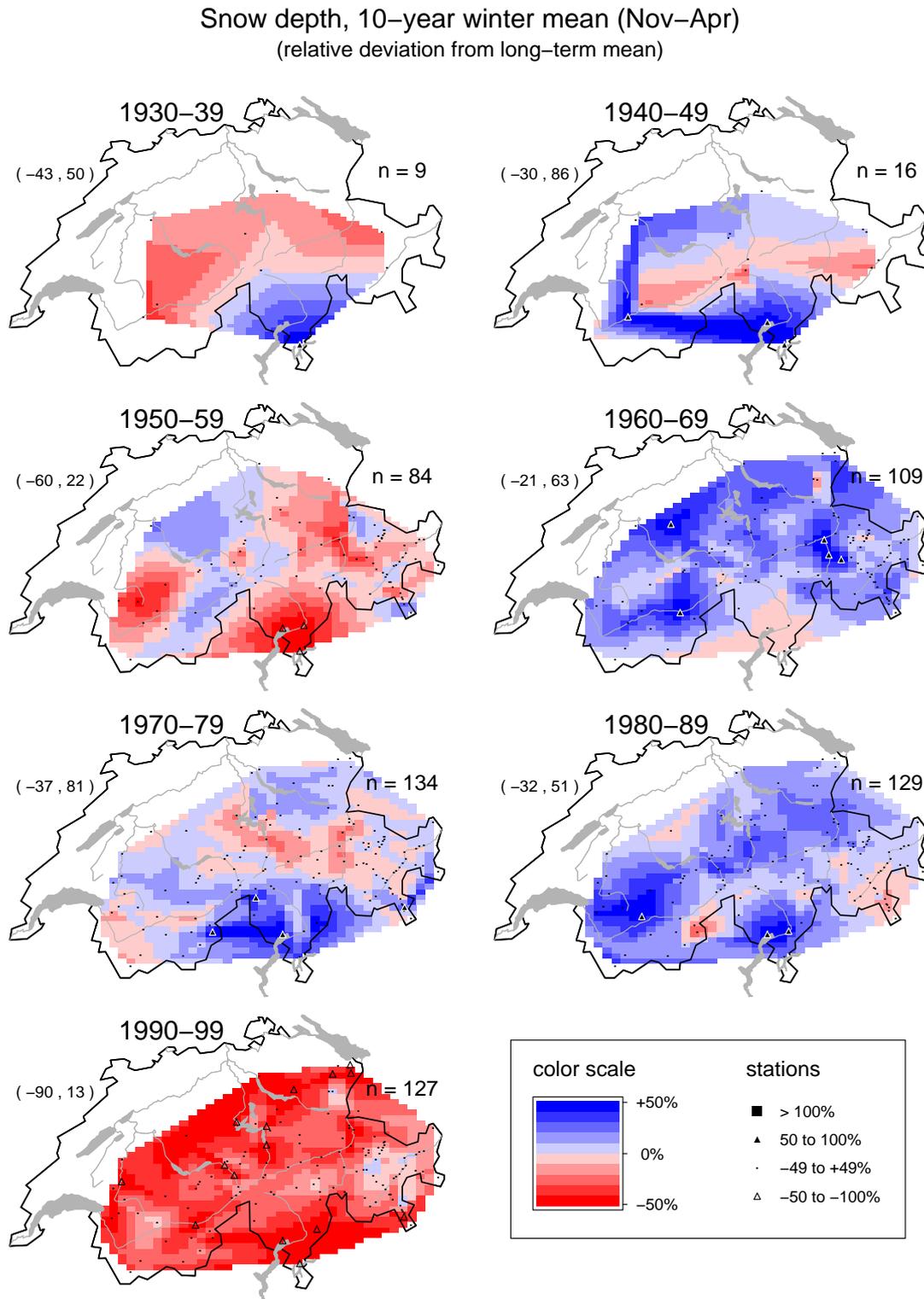
### 2.4.2 Trends of the average snow depth

First, the relative deviation of the 10-year-mean of HS compared to the long-term mean is analysed. Figure 2.9 contains seven maps for every decade from the 1930s to the 1990s, based on data of the entire winter period (Nov–Apr). For the first two decades the number of stations is very small and most stations are located at low levels. However, it can be assumed that the 1930s had generally below average snow (except in the south) and the 1940s had above average snow at lower altitudes, whereas the higher altitudes show slightly negative deviations from the long-term mean. From the 1950s on the number of stations significantly increased allowing more assured declarations. After the 1950s, with mostly below average snow, three decades with plenty of snow follow and the last decade, the 1990s, is again throughout and clearly below average. It is striking that the southern part of the Swiss Alps (R6 in Figure 2.1) often has different conditions than the north, except during the 1980s (when both regions were largely positive) and the 1990s (when both regions were clearly negative).

Looking at two-monthly part seasons, instead of the entire winter period, a much more diversified picture is attained. In early winter (Nov–Dec) the snow deficiencies are often more pronounced than for the entire winter (Figure 2.10). This is obvious during the 1940s (especially in the south), the 50s (mainly along the northern foothills), during the 60s and 70s (particularly in the south and south-east) and throughout the 80s (in most areas except the south). Contrary to that the 1990s had rather more snow in early winter compared to the entire winter (especially in the south) and also the 70s were snowier in most northern areas. For the mid winter months (Jan–Feb) no significant differences to the entire winter pattern can be found, but in late winter (Mar–Apr) clear deviations appear again.<sup>4</sup> The 1940s had generally little snow in late winter (especially

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<sup>4</sup> see additional illustrations at <http://www.slf.ch/research/snowtrends>



*Figure 2.9:* Relative HS-deviation (in %) of 10-year winter means (Nov–Apr) compared to the long-term mean. Dots show the availability of stations for interpolation; triangles and squares exceed the limits of the color scale (-50 to +50%). The numbers in brackets to the left of each plot give the data range and  $n$  is the number of stations.

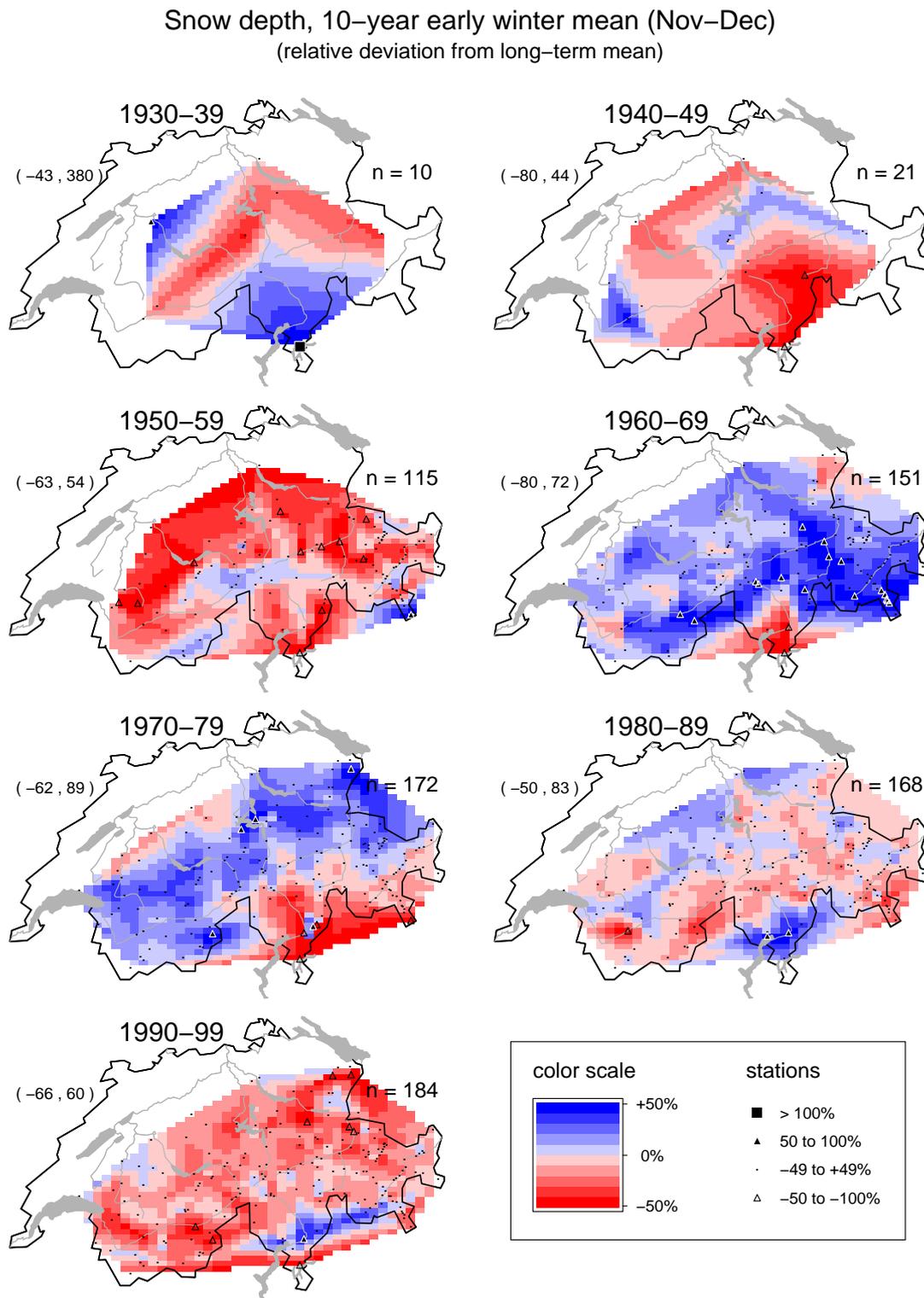


Figure 2.10: The same as Figure 2.9, but only for the early winter season (Nov–Dec).

in the south) and similar were the conditions during the 50s (with the south and west having particularly little snow). Late winter during the 60s was generally snowy, but shows clear, isolated deficits in the lower areas of the south and south-west. The 70s were throughout very snowy in spring (with peaks in the south) and also the 80s show above average spring snow in most parts. Whereas at high elevations the 90s in spring were close to average, low altitudes (< 1000 m a.s.l.) show strong deficiencies throughout Switzerland. Seasonal patterns resumed: snowy conditions prevailed mainly during the 1960s (mid winter), 70s (late winter) and 80s (mid and late winter), whereas little snow occurred during the 1940s (early and late winter), the 50s (early and late winter again) and during the 90s (particularly in mid and late winter).

Another important aspect is the snowiness during the Christmas – New Year period, since the ski tourism industry is especially vulnerable to meagre snow conditions during these days (Abegg, 1996) and emotionally a white Christmas is of high relevance to people in the lowlands (Rebetez and Barras, 1993). For this purpose the mean snow depth of the 10-day period from 20 – 29 December is analysed. The 1930s had plenty of snow in the lowlands, but slightly below average in the mountains. The 40s were generally meagre with particularly little snow in the south. The 50s show an interesting picture with high stations along the Alpine main divide having a lot of snow, whilst the lower regions (especially in the south) had large deficits. The 60s and 80s show both very snowy conditions, both in the lowlands and in the mountains, with one significant difference, however, for the southern areas. Whereas during the 60s the lowlands in the south had no snow at all, the 80s had record amounts of snow in the same areas. The 70s and 90s show both a complicating pattern with generally below average snow in the lower areas (especially during the 70s in the south) and slightly above average snow in some higher areas (especially during the 90s in the south). It can be summarized that during the Christmas – New Year period often little snow was recorded, especially at low levels, with major exemptions during the 1930s, 60s and 80s. Surprisingly, Christmas – New Year during the 1990s was rather snowier than the rest of the winter during this exceptionally lean decade.

These analyses lead to the conclusion that the degree of snowiness is based on three different priority levels: First priority is time. Periods with much or with little snow usually stretch across large areas. Second priority is space. Different regions can show more or less pronounced deviations from the general pattern. And third priority is altitude. Relative differences due to altitude within the same region and time period are weak. However, they are best visible during the 1990s, when stations at low levels had clearly below average snow and the higher the stations, the more they approached average conditions (Figure 2.11). Similar but far less pronounced tendencies can be

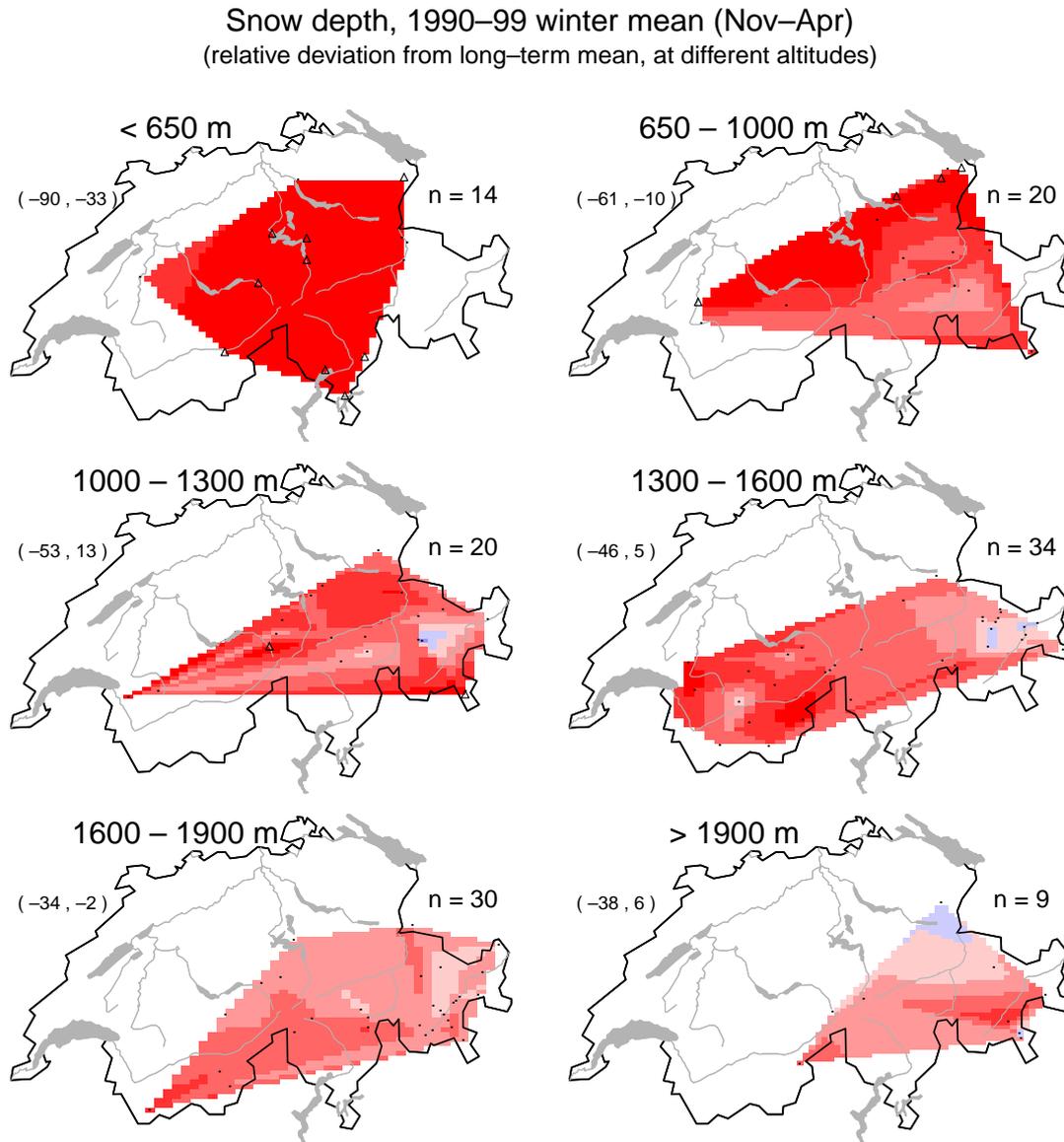


Figure 2.11: Similar as Figure 2.9 (same color scale), but only for the 1990s and splitted into different altitude zones.

found during the lean 1950s and rather the opposite is the case during the snowy 1960s, 70s and 80s, with low areas showing slight tendencies to higher relative values than high-altitude stations.

So far we were looking at HS-means over entire decades with the intention of having a certain smoothing of the high year-to-year variability and being able to detect medium-term trends. However, range and limits of decades are arbitrary and it is worthwhile to look at individual winters (Figure 2.12). During the 1960s especially 1963, 1968 (and 1970) were well above average, whereas 1964 was one of the poorest winters on record.

Snow depth, winter mean (Nov–Apr)  
(relative deviation from long-term mean)

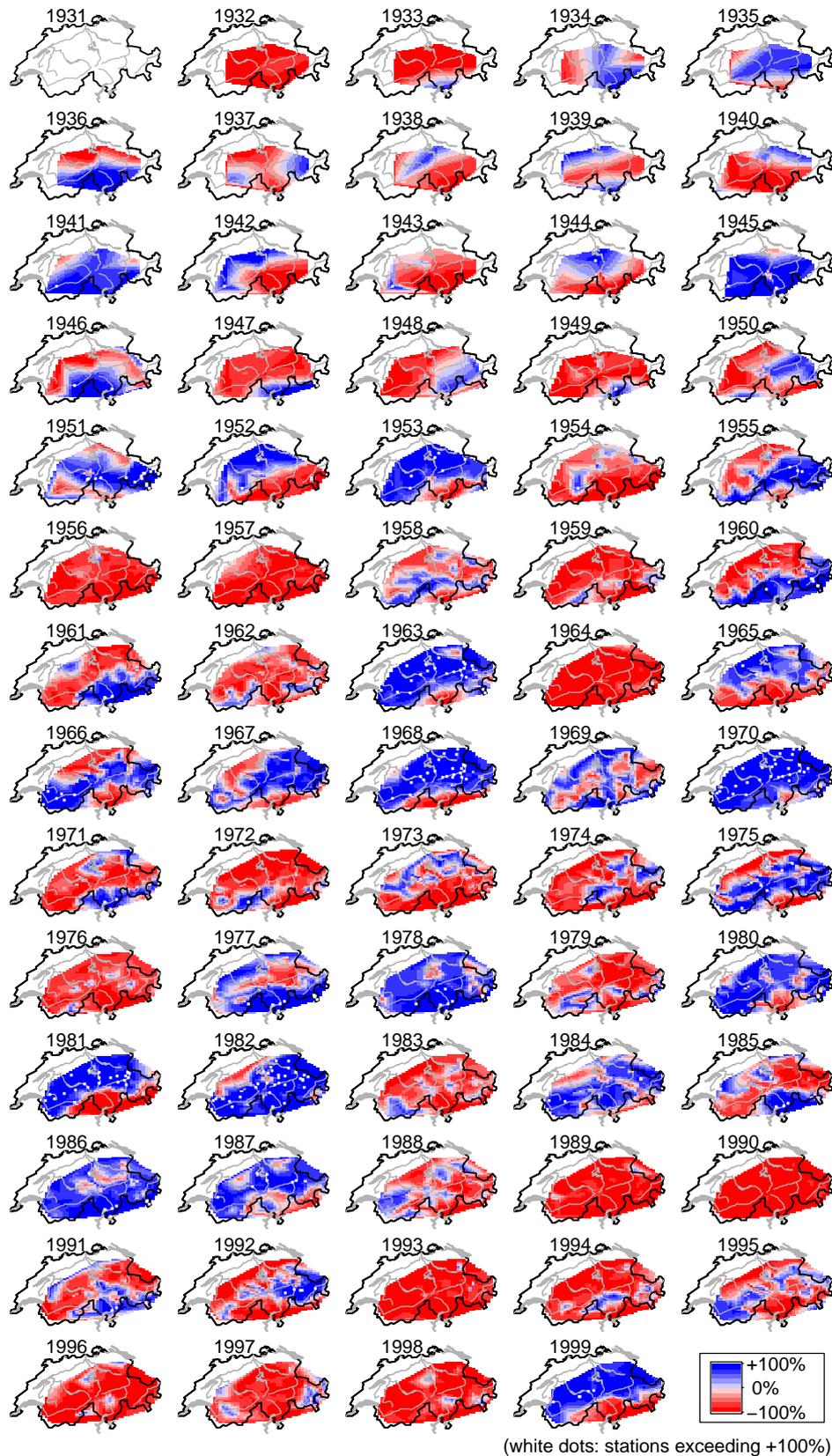


Figure 2.12: Similar as Figure 2.9, but for individual winters.

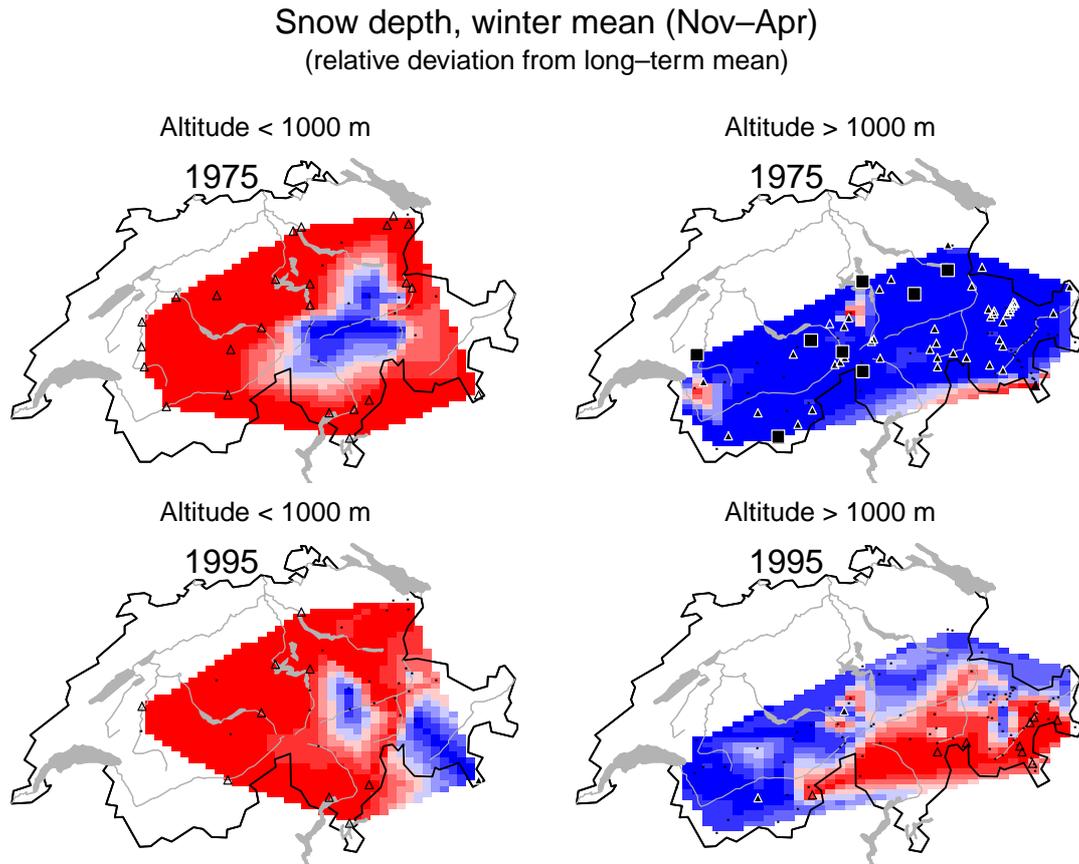


Figure 2.13: Similar as Figure 2.9 (same color scale), but only for 1975 and 1995 at two different altitude zones.

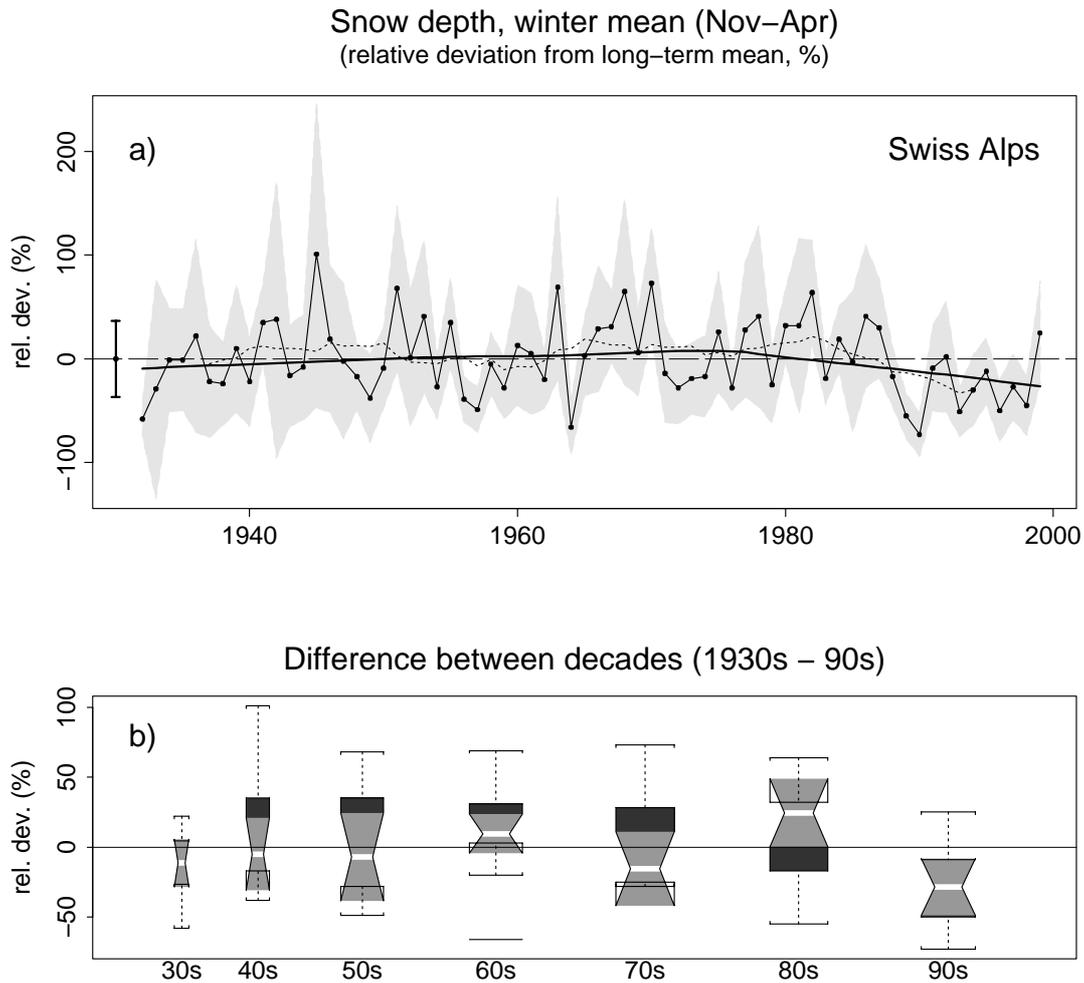
1980, 1981, 1982, 1986 and 1987 mainly contributed to the snowiness of the 1980s and the period with successively poor winters continuing through most of the 1990s already started in 1988. It is striking that five winters of the last decade (1990 – 99) are within the eleven least snowy winters of the past 69 years and also 1989 belongs to this group (Table 2.2). Regarding only the early winter period (Nov–Dec), the 1990s are more evenly distributed over the ranking list and only 1990 and 1995 had particularly little snow. The ranking for mid and late winter produces again a similar picture as for the entire winter period with many years of the 1990s being close to the tail of the list. Relative altitudinal variations are generally not strong, but 1975 and 1995 are two illustrative exceptions (Figure 2.13). In 1975 high elevations had clearly above average snow, whereas low stations had largely very little, except for the central areas. In 1995 stations below 1000 m a.s.l. show clear negative deviations from the average (except in the south-east), whereas stations above 1000 m a.s.l. show exactly the opposite pattern: above average snow in most parts, except in the south-eastern areas.

Table 2.2: Swiss average snowiness of individual winters (Nov–Apr) from 1931 – 1999 expressed by the relative HS-deviation (in %) from the long-term mean. The number of stations and the standard deviation are indicators for the reliability and variance of the data. The ten snowiest winters are in italics and numbered 1–10 in front of the winter figure, the ten least snowy winters are bold and numbered 1–10 behind the winter figure.

<i>Winter</i>	<i>No. of stat.</i>	<i>% of mean</i>	<i>St. dev. (%)</i>
1931	0	—	—
<b>1932</b> <sup>3</sup>	9	-58	17
1933	9	-29	106
1934	9	-1	50
1935	9	-1	49
1936	9	22	93
1937	10	-22	54
1938	10	-24	40
1939	10	10	62
1940	12	-22	43
1941	12	35	38
<sup>10</sup> 1942	14	38	134
1943	14	-16	49
1944	16	-8	51
<sup>1</sup> 1945	16	101	148
1946	32	19	71
1947	32	-2	75
1948	38	-17	32
<b>1949</b> <sup>10</sup>	34	-38	43
1950	37	-9	39
<sup>4</sup> 1951	45	68	80
1952	51	1	66
<sup>7</sup> 1953	55	41	74
1954	78	-27	31
1955	85	35	44
<b>1956</b> <sup>9</sup>	92	-39	22
<b>1957</b> <sup>7</sup>	89	-49	22
1958	93	-5	30
1959	94	-28	30
1960	104	13	58
1961	103	5	59
1962	103	-20	28
<sup>3</sup> 1963	106	69	89
<b>1964</b> <sup>2</sup>	104	-66	27
1965	112	3	38

<i>Winter</i>	<i>No. of stat.</i>	<i>% of mean</i>	<i>St. dev. (%)</i>
1966	114	29	61
1967	119	31	35
<sup>5</sup> 1968	122	65	90
1969	119	6	42
<sup>2</sup> 1970	128	73	54
1971	124	-14	47
1972	133	-28	35
1973	135	-19	35
1974	133	-17	39
1975	136	26	58
1976	136	-28	22
1977	135	28	65
<sup>7</sup> 1978	132	41	87
1979	133	-25	37
1980	133	32	36
1981	133	32	85
<sup>6</sup> 1982	132	64	50
1983	127	-19	25
1984	130	19	32
1985	130	-3	68
<sup>7</sup> 1986	131	41	69
1987	125	30	48
1988	131	-17	29
<b>1989</b> <sup>4</sup>	130	-55	22
<b>1990</b> <sup>1</sup>	118	-73	21
1991	130	-9	41
1992	131	2	54
<b>1993</b> <sup>5</sup>	131	-51	24
1994	130	-30	34
1995	128	-12	32
<b>1996</b> <sup>6</sup>	100	-50	30
1997	92	-27	32
<b>1998</b> <sup>8</sup>	90	-45	29
1999	89	25	50

A time series plot of the annual relative deviation from the long-term mean, averaged over all stations, is shown in Figure 2.14a. Particularly snowy winters with more than +50% of the average were 1945, 1951, 1963, 1968, 1970 and 1982 (see also Table 2.2). On the opposite, the least snowy winters with less than -50% of the average were 1932, 1964, 1989, 1990, 1993 and 1996. Very typical are the large year-to-year variations with the most impressive example being the immense drop from 1963 (the third snowiest winter) to 1964 (the second poorest winter). Obviously winters with much or little snow are seldom grouped together and in every second case after a year with below average snow follows a year with above average snow. Even in more than 60%



*Figure 2.14:* (a) Relative HS-deviation (in %) of annual winter mean (Nov–Apr) compared to the long-term mean, 11-year moving average (dotted line), lowess-smoother ( $f = 0.67$ , thick line) and  $\pm$  one standard deviation (grey area, contains two thirds of all data). The vertical bar on the left stands for  $\pm$  one standard deviation of the whole sample (average for the entire Swiss Alps from 1932 – 1999), which is not exceeded by the long-term trend.

(b) Difference between decades (1930s – 90s) displayed by notched boxplots. Notches on two boxes (grey areas) which do not overlap indicate a difference at a 95%-significance level. The box width is proportional to the number of observations (1930s: 9 stations, 1970s: 133 stations).

of all cases the direction towards increasing or decreasing snow changes from year to year. Clusters of successive years with above average snow can be found in the late 60s and with short interruptions from the late 70s till the mid 80s. Accumulations of years with below average snow are recorded in the late 40s, late 50s till early 60s, early 70s and from the late 80s through most of the 90s.

Compared to the long-term mean and to all other decades the 1990s are strikingly low. Student's t-test proves that the 1990s-mean ( $-27\%$ ) lies far outside of the 95%-confidence interval ( $-14.1\%$  to  $+13.4\%$ ) and thus significantly differs from the long-term mean. Also the 1960s ( $+13.5\%$ ) are slightly outside of the confidence band — however, with a positive deviation — whereas the 1980s ( $+12.4\%$ ) and 1930s ( $-12.9\%$ ) remain just inside. The necessary assumptions to perform a t-test (normally distributed, independent and not autocorrelated observations) are well fulfilled. Testing the 1990s against the other decades (paired two-sample t-test) reveals that the 1990s differ significantly from the 1980s (p-value = 0.0367) and from the 1940s (p-value = 0.0296), whereas the 1960s (p-value = 0.0526) are just beyond the 95%-confidence level. All other decades show no significant deviation from the 1990s. It seems a bit surprising that according to this test the 1940s are more different to the 90s than the 1960s, but it has to be born in mind that the mean for the 1940s is based on considerably less stations (22) than the 1960s (110) and that extreme values (1945 very high, 1964 very low) have a stronger weight for the mean calculation than for the median. Notched boxplots (based on the variance of the *median* distribution) drawn for all decades show that the 1980s and 1960s significantly differ from the 1990s, whereas the 1940s don't (Figure 2.14b).

Of course the Swiss average plotted in Figure 2.14 is spatially not evenly spread, but is biased towards those regions with most stations (particularly R5). As can be expected, different regions do not show exactly the same behaviour as the Swiss average (Figure 2.15 and 2.16). Due to the lack of a sufficient number of stations in the single regions, for the first up to 25 years (R3) no reliable statements can be made. The entire North Slope of the Swiss Alps (**R1 – R3**) behaves very similarly and is combined in one plot (Figure 2.15a). 1953 (not 1951!), 1963, 1968, 1970, 1981, 1987 and 1999 are the outstanding years with a lot of snow, whereas 1964 and 1990 were the years on the bottom end. In this homogeneous region the 1990s, the 1980s and (only just) also the 1960s differ significantly from the long-term average. According to the paired two-sample t-test for the means only the 1980s show significant deviations from the 1990s (p-value = 0.0351). However, the notched boxplots reveal significant median deviations also for the 1960s (Figure 2.15b). **R4** (Figure 2.16a), an interior area between two main branches of the Alps, behaves already quite differently with 1945 and 1966 (not 1968!) being the snowiest years and again 1964 and 1990 being the poorest years. Worth mentioning is the persistent up and down from year to year from the mid 60s to the mid 80s until in 1986 the big drop begins towards a nearly continuous level below average throughout the 90s. Boxplots for different decades show that the 1980s are just about significantly higher to the 90s. **R5** (Figure 2.16b) follows again closer the line of

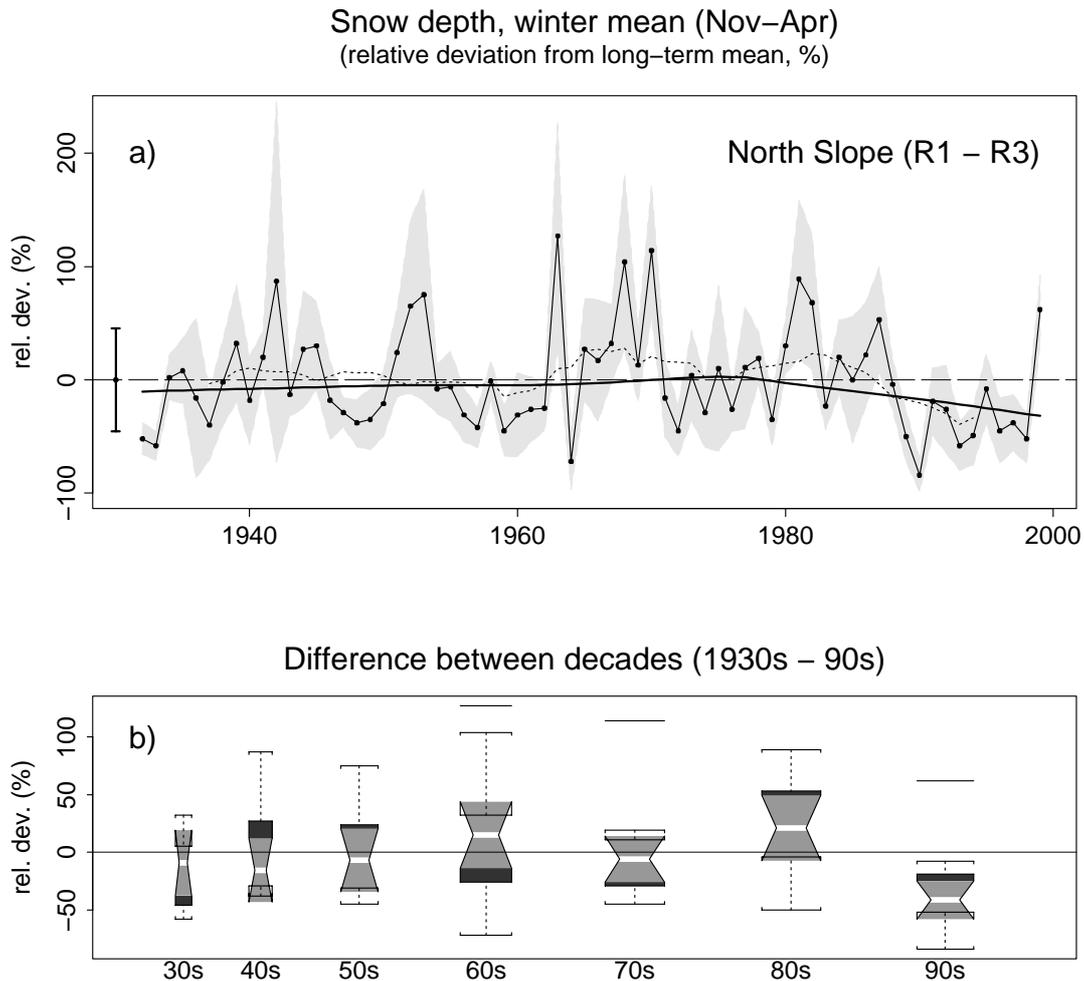


Figure 2.15: The same as Figure 2.14, but only for the North Slope of the Swiss Alps (R1 – R3).

R1 – R3, but because of the tendency to inner-alpine climate in the southern areas has its own characteristics. In addition to the same snowy years as for R1 – R3 come 1945, 1951, 1955, 1975, 1982 (instead of 1981) and 1992 (which is exceptionally high compared to all other regions). 1957, 1979 and 1996 are additional years with markedly little snow. Further noticeable is the very low period between 1956 and 1962, the constant increase over five years from 1971 to 1975 and the strong drop from 1987 to 1990. According to the boxplots no decade differs significantly from the 1990s. **R6** (Figure 2.16c), the only region entirely south of the Alps, has its completely own line: 1945, 1961, 1978, 1986 and 1991 are the dominant peaks beside most other years being below or only slightly above average. Also here 1964 and 1990 are strongly negative years, together with 1981, 1989 and 1993 and again boxplots show no

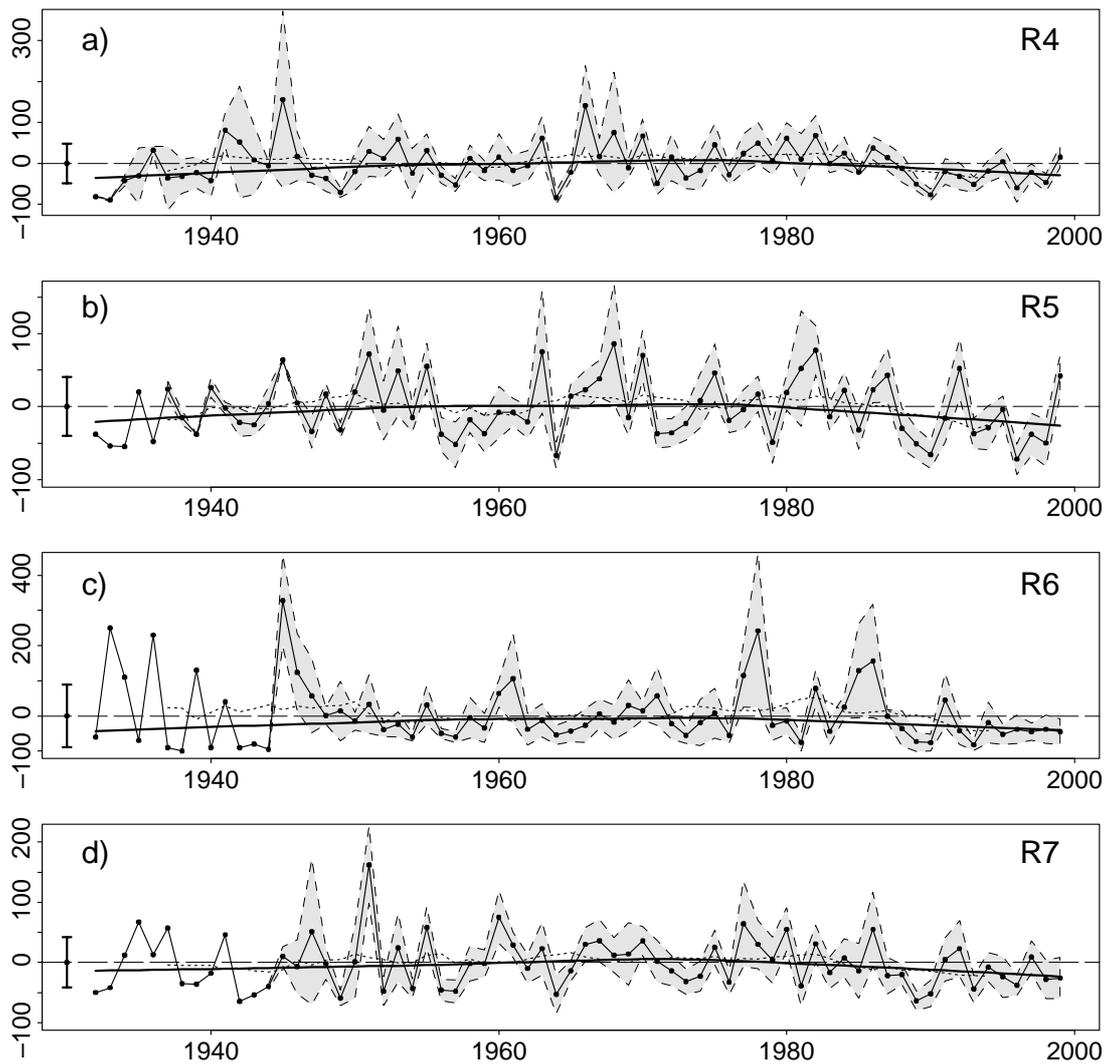


Figure 2.16: The same as Figure 2.14a, but for R4, R5, R6 and R7. Most regions have only one station from the very beginning (1932), which does not allow to draw a standard deviation. Note the different scales of the y-axis.

significant differences between any decades. **R7** (Figure 2.16d) to some degree resembles R5 (1951, 1955 and 1992 being strongly positive; 1957, 1964 and 1990 being strongly negative), but shows also similarities to R6 (1986 well above; 1981 and 1989 well below average). Apart from that R7 follows again an own line having additionally 1947, 1960, 1977 and 1980 as snowy years and with 1949 a year with very little snow. Boxplots for different decades show that the 1960s are just about significantly higher than the 90s. These regional analyses clearly demonstrate the climatological diversity of the Swiss Alps.

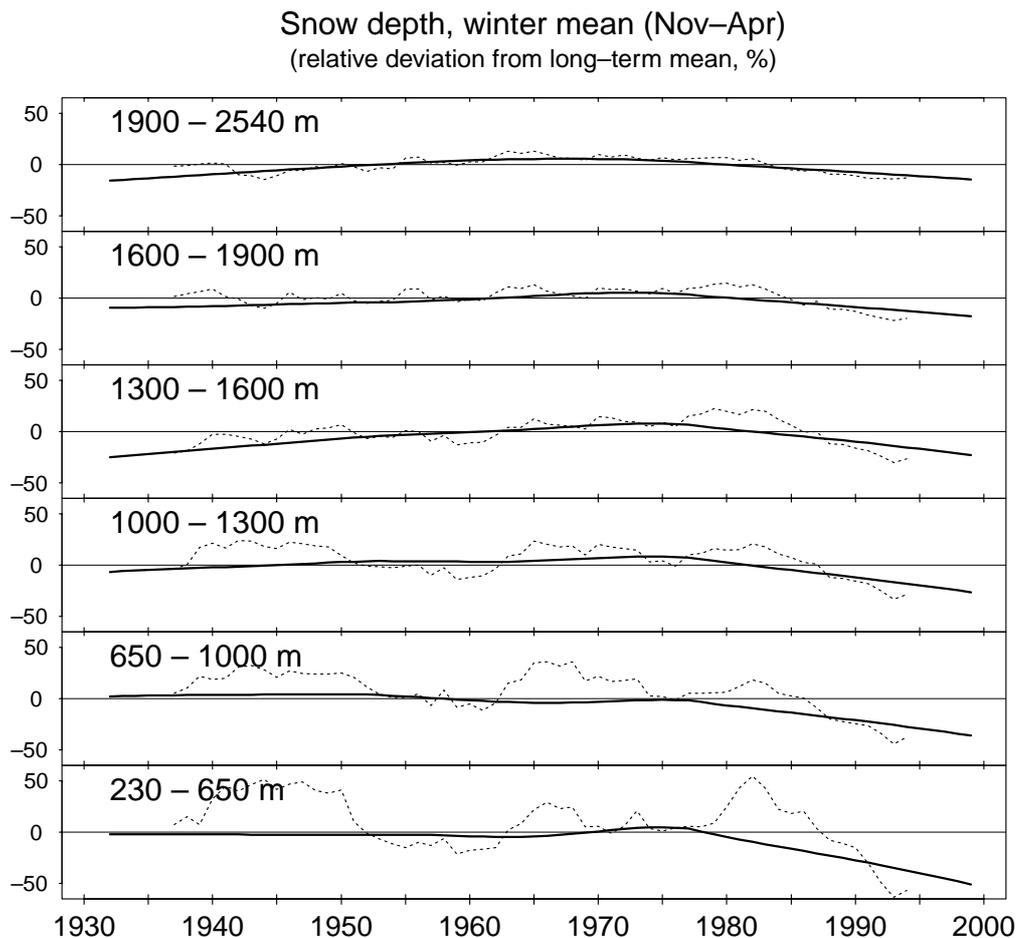


Figure 2.17: Relative HS-deviation (in %) of the annual winter mean (Nov–Apr) compared to the long-term mean. Drawn are the 11-year moving average and the lowess-smoothed long-term trend for different altitude zones, based on data of the entire Swiss Alps (1932 – 1999).

In addition to regional variations, trends are not uniformly distributed with altitude (Figure 2.17). For the entire Swiss Alps and the whole winter period, high elevations (> 1600 m a.s.l.) show since the 1930s a very slight increase culminating in the early 1960s, followed by a 20-year period remaining on this high level and then a gradual decrease towards the end of the century ending somewhat below the initial start-up level. On the other hand, low elevations (< 1000 m a.s.l.) show much more variability: a very snowy period during the 1940s is followed by the lean 1950s, then again the snowy 1960s, about average 1970s and after a final climax in the early 1980s a marked drop towards unprecedented low values during the 1990s. Test statistics prove that for low-lying stations the 1990s show significant differences (on a 95%-confidence level) to the 1940s, 1960s and 1980s (Table 2.3), whereas for high-altitude stations no significant differences can be found between any decades. Furthermore, the 1940s

Table 2.3: Relative HS-deviation of 10-year periods (in %) from the long-term mean of all stations below 1000 m a.s.l. (second column). The 95%-confidence interval (−22.7% to +29.5%) is far outreached by the 1990s (strong negative deviation) and 1940s (strong positive deviation; bold numbers). The further columns show a comparison between different decades expressed by the p-value of a paired two-sample t-test. P-values < 0.05 (bold) indicate that the two corresponding decades differ significantly on a 95%-confidence level.

	<i>rel. dev. (%)</i>	<i>p-values</i>					
		<i>1980s</i>	<i>1970s</i>	<i>1960s</i>	<i>1950s</i>	<i>1940s</i>	<i>1930s</i>
<b>1990s</b>	<b>−44.6</b>	<b>0.016</b>	0.118	<b>0.040</b>	0.097	<b>0.012</b>	0.091
<b>1980s</b>	18.4		0.523	0.951	0.357	0.344	0.549
<b>1970s</b>	0.9			0.486	0.829	0.317	0.939
<b>1960s</b>	20.7				0.311	0.565	0.293
<b>1950s</b>	−5.3					0.099	0.834
<b>1940s</b>	<b>44.3</b>						0.191
<b>1930s</b>	−10.7						

(+44.3%) and 1990s (−44.6%) of low stations lie far beyond the 95%-confidence band (−22.7% to +29.5%) of the long-term average (Table 2.3), while some decades of high stations only slightly exceed the confidence limits (−9.1% to +8.0%): 1990s (−15.6%), 1940s (−9.9%) and 1960s (11.2%). The strong decreasing trend since the early 1980s at low elevations can be found throughout all regions R1 – R7. R4 shows even a strong and continuous downward trend at high elevations since the 1960s. Different part seasons reveal that the downward trend at low elevations is best visible in mid winter (Jan–Feb), whereas in early and late winter long-term trends are not that clear. However, this may be simply because low elevations only irregularly receive snow before and after mid winter. Averaged across all altitudes in early winter (Nov–Dec) no significant differences between any decades exist, in mid winter (Jan–Feb) the 1960s are significantly higher than the 90s and in late winter (Mar–Apr) the 1980s are significantly higher than the 90s (according to the boxplot-median distribution).

### 2.4.3 Trends of the duration of snow cover and related parameters

#### Duration of continuous snow cover (d0)

Time series of the duration of snow cover reveal large variability for different stations, regions and altitudes. The general pattern for d0 (continuous duration of HS > 0 cm) is that high stations (approx. > 1600 m a.s.l.) and low stations (approx. < 1000 m a.s.l.) are fairly constant over the last 70 years, whereas at mid altitudes (about 1000 – 1600 m a.s.l.) a strong increase culminating in the early 1980s was followed by a marked

## Duration, beginning and end of continuous snow cover

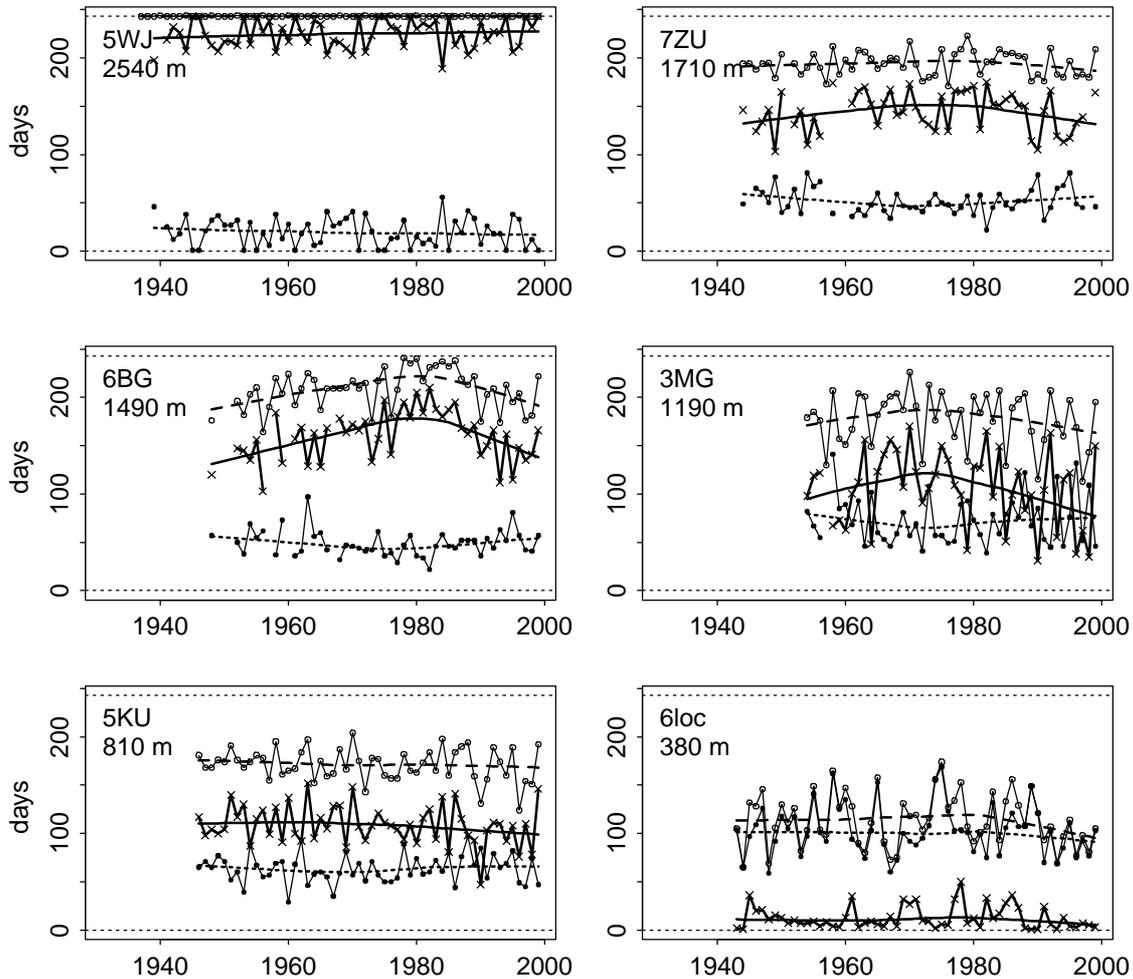


Figure 2.18: Duration ( $\times$ ), beginning ( $\bullet$ ) and final date ( $\circ$ ) of continuous snow cover during the last 50 – 60 years for six exemplary stations at different altitudes: Weissfluhjoch (2540 m, 5WJ), Zuoz (1710 m, 7ZU), Bosco/Gurin (1490 m, 6BG), St. Margrethenberg (1190 m, 3MG), Küblis (810 m, 5KU) and Locarno (380 m, 6loc). Drawn are annual values and lowess-smoothed long-term trends. The y-axis shows the number of days for the duration and the number of days since 1 October (lower dotted line) for the beginning and end of snow cover. The upper dotted line indicates the latest possible date covered by data (31 May).

decrease towards the end of the century (Figure 2.18). However, exceptions are plentiful and in dry interior areas (Upper Engadine, southern Valais) the boundary between mid- and high-altitude characteristics reaches up to 1900 m a.s.l. Also low stations in narrow foothill valleys often resemble more their higher neighbours (with a marked decrease since the 1980s) and only the low-lying foreland stations show an indifferent picture or only a slight tendency to shorter snow duration in recent years. At least this is found for absolute values; looking at relative deviations from the long-term mean reveals a slightly different picture. As for the HS-winter mean the decreasing

trend since the early 1980s gets more pronounced from high- to low-altitude stations and looks near identical as in Figure 2.17. This affinity is not surprising, since the correlation between HS-winter mean (relative deviation from long-term mean) and  $d0$  (relative deviation from long-term mean) is 0.87 averaged for the entire Swiss Alps. At low elevations small and hardly visible absolute trends obviously turn into large and noticeable relative changes.

### **Beginning (b0) and end (e0) of snow cover**

Associated with the duration is the time of beginning (b0) and end (e0) of the snow cover. Whereas at high-altitude stations the continuous snow cover tends to build-up rather earlier, at low and especially at mid altitudes the snow cover often starts later in recent years (Figure 2.18). However, trends are very weak and altogether b0 is fairly constant over the last 70 years. On the other hand, e0 shows a clearer trend towards earlier snow melting during the 1980s and 90s. In fact most stations at all altitudes reveal this behaviour and there are only few exceptions (Davos region, Lower Engadine and low-lying stations in narrow, shady valleys). This implies that the generally shorter duration of snow cover is mainly caused by earlier snow melting than later first snowfalls. Controversial to that the relative deviations from the long-term mean indicate that b0 is rising sharper (especially at high and mid altitudes; Figure 2.19) and e0 remains virtually constant (with a slight decreasing tendency at low altitudes; Figure 2.20). However, the 11-year moving average curves remain within  $\pm 10\%$  of the long-term mean, which is little variability on the absolute scale. Further, during the 1930s and 40s the moving average and lowess-smoother are calculated only from one or two long-term stations, whereas the station density in the following years increases up to 20 – 30 stations per elevation level; only elevations  $> 1900$  m a.s.l. reach never more than nine stations (cf. Figure 2.4). Because of the variable amount of stations each year, the large regional variability of snow duration as such and changing altitude zones in different regions, it is problematic to calculate Swiss averages; careful analyses of individual stations (such as for Figure 2.18) seem more meaningful.

### **Different HS-thresholds for duration (d20 – d70), beginning (b20 – b70) and final date (e20 – e70) of snow cover**

Time series of different HS-thresholds for the duration (d20 – d70), beginning (b20 – b70) and final date (e20 – e70) are largely parallel to the curves with the 0 cm-threshold, but have smaller absolute values (Figure 2.21). However, low-lying stations do seldom or never reach high HS-thresholds and therefore d50 – d70 are usually zero

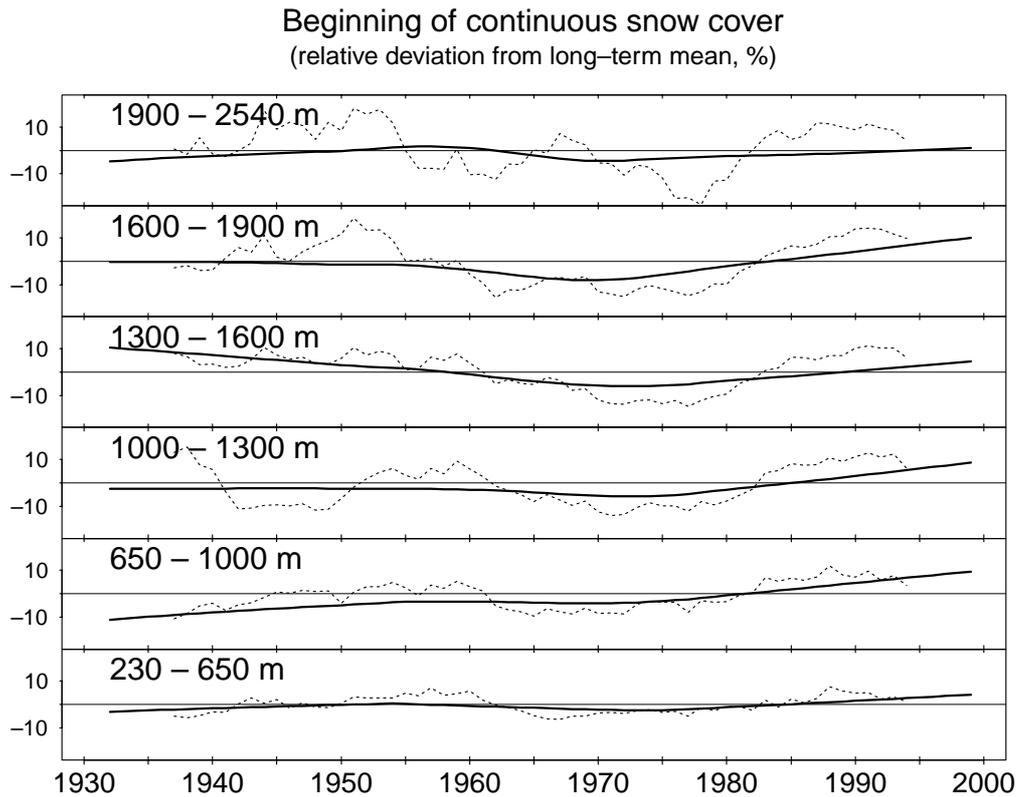


Figure 2.19: Beginning of continuous snow cover (b0): relative deviation (in %) from the long-term mean. Drawn are the 11-year moving average and the lowest-smoothed long-term trend for different altitude zones, based on data of the entire Swiss Alps (1932 – 1999).

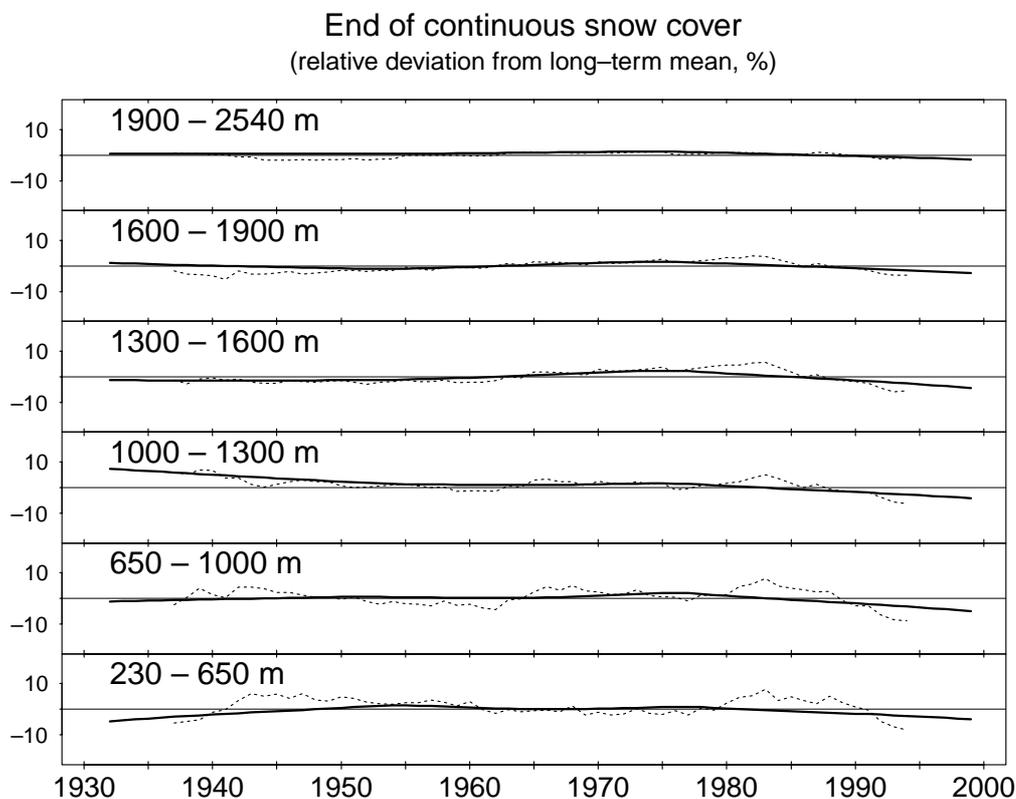


Figure 2.20: The same as Figure 2.19, but for the final date of the snow cover (e0).

## Duration of snow cover above various HS-thresholds

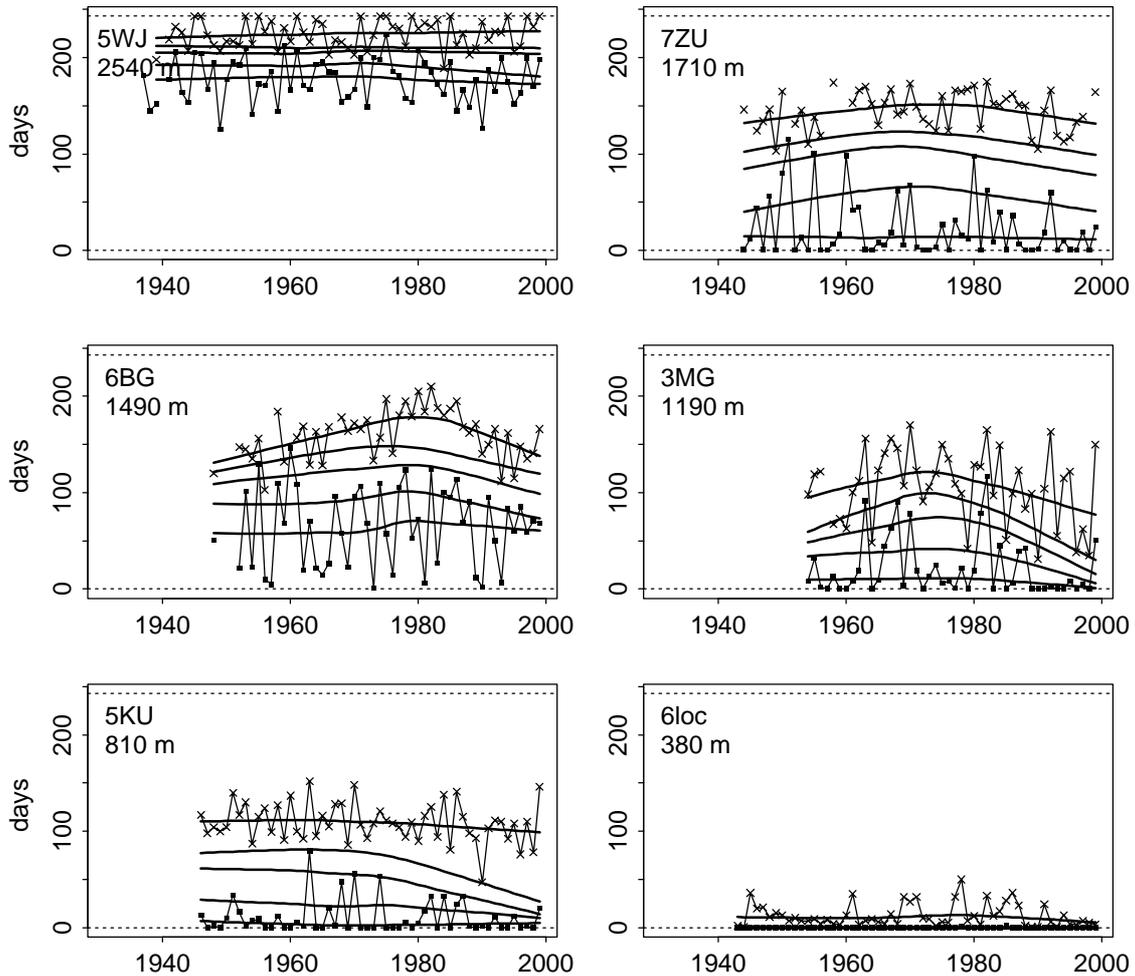


Figure 2.21: Duration of snow cover above several HS-thresholds for the same selection of stations as in Figure 2.18. The topmost curve shows annual values ( $\times$ ) and the lowest-smoothed long-term trend of d0 (duration with HS  $>$  0 cm). Below follow three lowest-smoothed trend lines of d20 (HS  $>$  20 cm), d30 (HS  $>$  30 cm) and d50 (HS  $>$  50 cm). At the bottom are the annual values ( $\blacksquare$ ) and the lowest-smoothed long-term trend of d70 (HS  $>$  70 cm).

and b50 – b70 and e50 – e70 can not be calculated. Some stations (e.g., 5KU) show stronger negative trends for high HS-thresholds, what implies that large snow depths were less frequent in the 1980s and 90s. The median of the relative deviations from the long-term mean of the 1990s along the North Slope of the Swiss Alps (R1 – R3) is constantly falling from d0 – d70 (Table 2.4). Also e0 – e70 is always negative (earlier snow melting) and falling. However, b0 is in fact negative too (what means *earlier* first snowfalls) and only from b20 – b70 the relative deviations are slightly positive (later first snowfalls, Table 2.4). There are few significant differences between various decades. The major exemption is d0 in the eastern Swiss Alps (R5 and R7), where the 1960s and 70s are significantly higher than the 1990s.

*Table 2.4:* Relative deviation from the long-term mean (in %), median of the 1990s, R1–R3 (North Slope of Swiss Alps). Parameters: d0 – d70 (duration of snow cover with HS > 0 ... 70 cm), b0 – b70 (beginning of snow cover with HS > 0 ... 70 cm), e0 – e70 (end of snow cover with HS > 0 ... 70 cm). Positive percentage for the beginning of snow cover means later first snowfall, negative percentage for the end of snow cover means earlier snow melt.

	<i>Duration (%)</i>	<i>Beginning (%)</i>	<i>End (%)</i>
HS > 0 cm	–16	–6	–1
HS > 20 cm	–30	+2	–3
HS > 30 cm	–34	+1	–5
HS > 50 cm	–57	+5	–8
HS > 70 cm	–70	+4	–10

### Minimum snow depth during 100 days (hs100d)

Trends for the minimum snow depth during 100 days (hs100d) can be classified into three altitude zones again: Stations higher than about 1300 m a.s.l. are usually above the 30 cm-threshold, the critical lower limit for profitable skiing tourism. Since about 1950 hs100d generally increased over the following three decades up to the culmination point at around 1980 and then dropped until in the late 1990s a similar level like 1950 was reached again (Figure 2.22). There is hardly any exception to this behaviour; only very few stations show a fairly constant trend during the last 5 – 6 decades and not one station shows an increasing trend during the 1980s and 90s. However, in the interior areas the critical 30-cm limit reaches up to 1800 m a.s.l. Below that and down to about 1000 m a.s.l. hs100d fluctuates in all regions around the 30 cm-limit without big variations. The decreasing trend since 1980 is only weak. However, expressed as a relative deviation from the long-term mean, low and mid altitudes show a stronger decline than high altitudes. Stations below about 800 m a.s.l. usually do not have snow during 100 days per winter.

#### 2.4.4 Trends of snowfall days and heavy snowfall events

##### Number of days with snowfall (dhn)

The number of days with snowfall (HN > 0 cm) during one winter (Nov–Apr) varies from 0 days at Lugano (275 m a.s.l.) in the winters 1968, 1988, 1989, 1990, 1993 and 1998 to 124 days on Säntis (2500 m a.s.l.) in winter 1966. The relative annual dhn-distribution (deviation from the long-term mean) is similar as for the HS-mean (Figure 2.12), but some years show a greater spatial diversity. In such cases dhn usually shows stronger positive deviations than the HS-mean indicating that these winters had many days, but only with little snowfall. As for most other snow parameters from

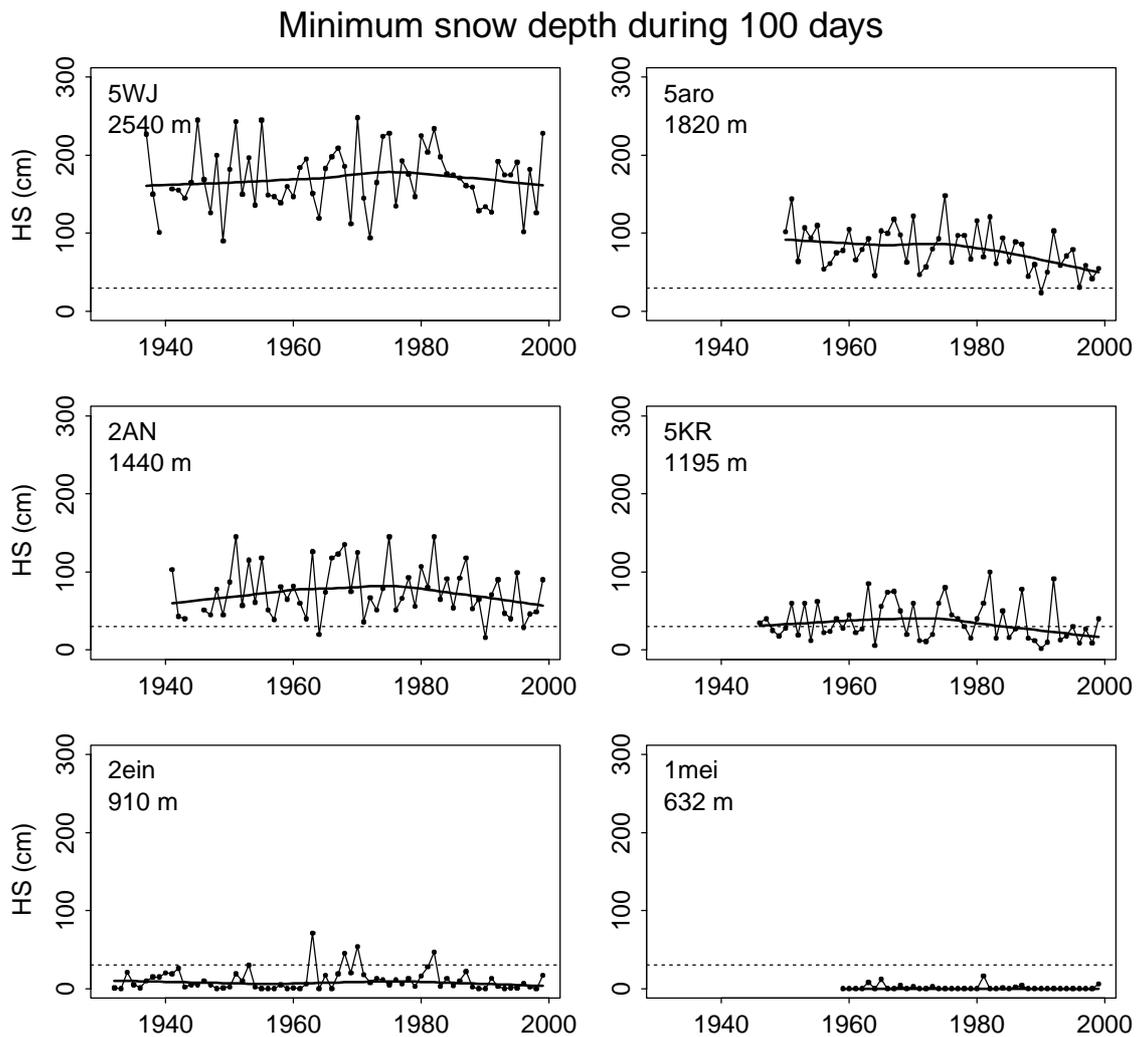
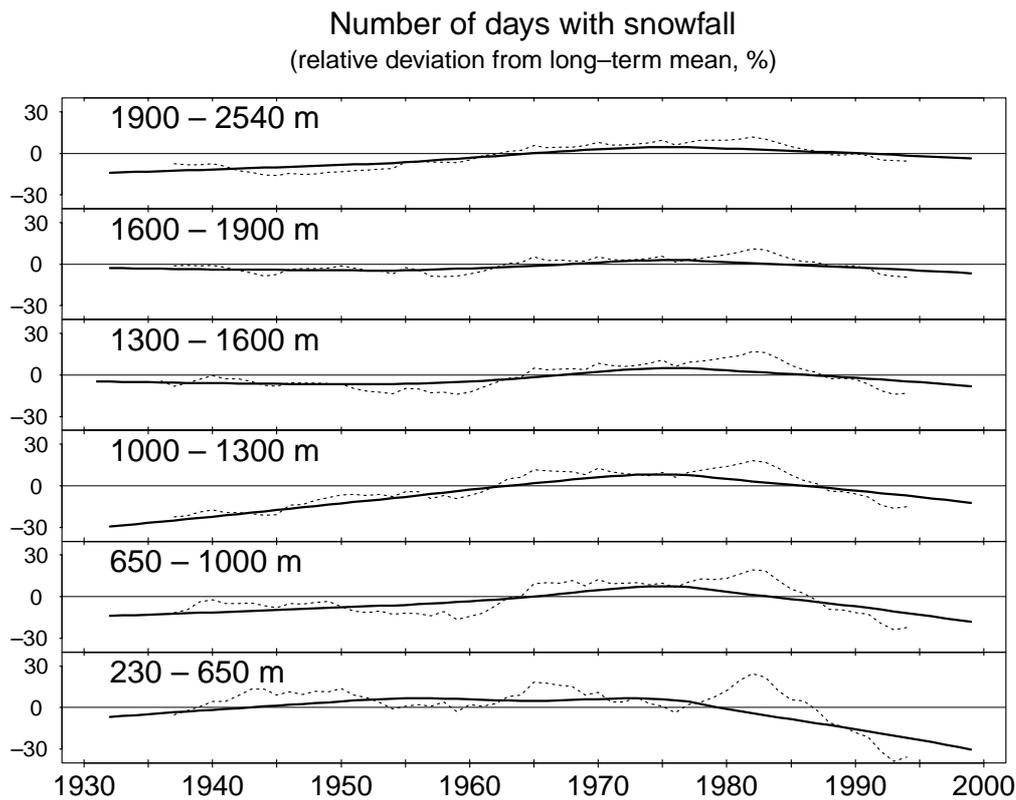


Figure 2.22: Time series of minimum snow depth during 100 days (hs100d) for six exemplary stations at different altitudes: Weissfluhjoch (2540 m, 5WJ), Arosa (1820 m, 5aro), Andermatt (1440 m, 2AN), Klosters (1195 m, 5KR), Einsiedeln (910 m, 2ein) and Meiringen (632 m, 1mei). Drawn are annual values and lowess-smoothed long-term trends. The dotted line indicates the 30 cm level (critical limit for profitable skiing tourism).

1960 – 1980 days with snowfall were mainly above average and then a decreasing trend began. This trend to less snowfall days becomes stronger with decreasing altitude (Figure 2.23). Absolute values are surprisingly level for a large elevation zone of about 1200 – 1800 m a.s.l. (50 – 60 days per winter, Figure 2.24). In all regions the 1980s are significantly higher than the 90s, in all except one region (R7) also the 60s are higher and in some regions (R1–R3, R6) even the 70s are significantly higher than the 90s.



*Figure 2.23:* Number of days with snowfall (Nov–Apr): relative deviation (in %) from the long-term mean. Drawn are the 11-year moving average and the lowess-smoothed long-term trend for different altitude zones, based on data of the entire Swiss Alps (1932 – 1999).

### Number of days with HN > 10, 20 and 50 cm (dhn10 – dhn50)

Low-lying stations do not always, rarely or never reach daily new snowfalls greater than 10, 20 or 50 cm every winter. The recorded maxima are: for dhn10 78 days (Gd-St-Bernard, 2479 m, winter 1978), for dhn20 39 days (Gd-St-Bernard, winter 1977) and for dhn50 14 days (Säntis, 2500 m, winter 1958). Long-term trends are similar as for dhn but become weaker with higher thresholds (Figure 2.24). Whereas for dhn10 only the 1980s differ significantly from the 90s, for dhn20 no decade differs significantly from another anymore and — because of the very few events — for dhn50 no long-term changes can be determined at all.

### Heavy snowfall events (HN3max)

The annual maximum of HN3 (the HN sum of three successive days) is taken as an indicator for heavy snowfall events. The recorded HN3-maximum is 295 cm at Simplon Hospiz (2000 m a.s.l.) in winter 1986. Compared to the HS-mean (Figure 2.9) the

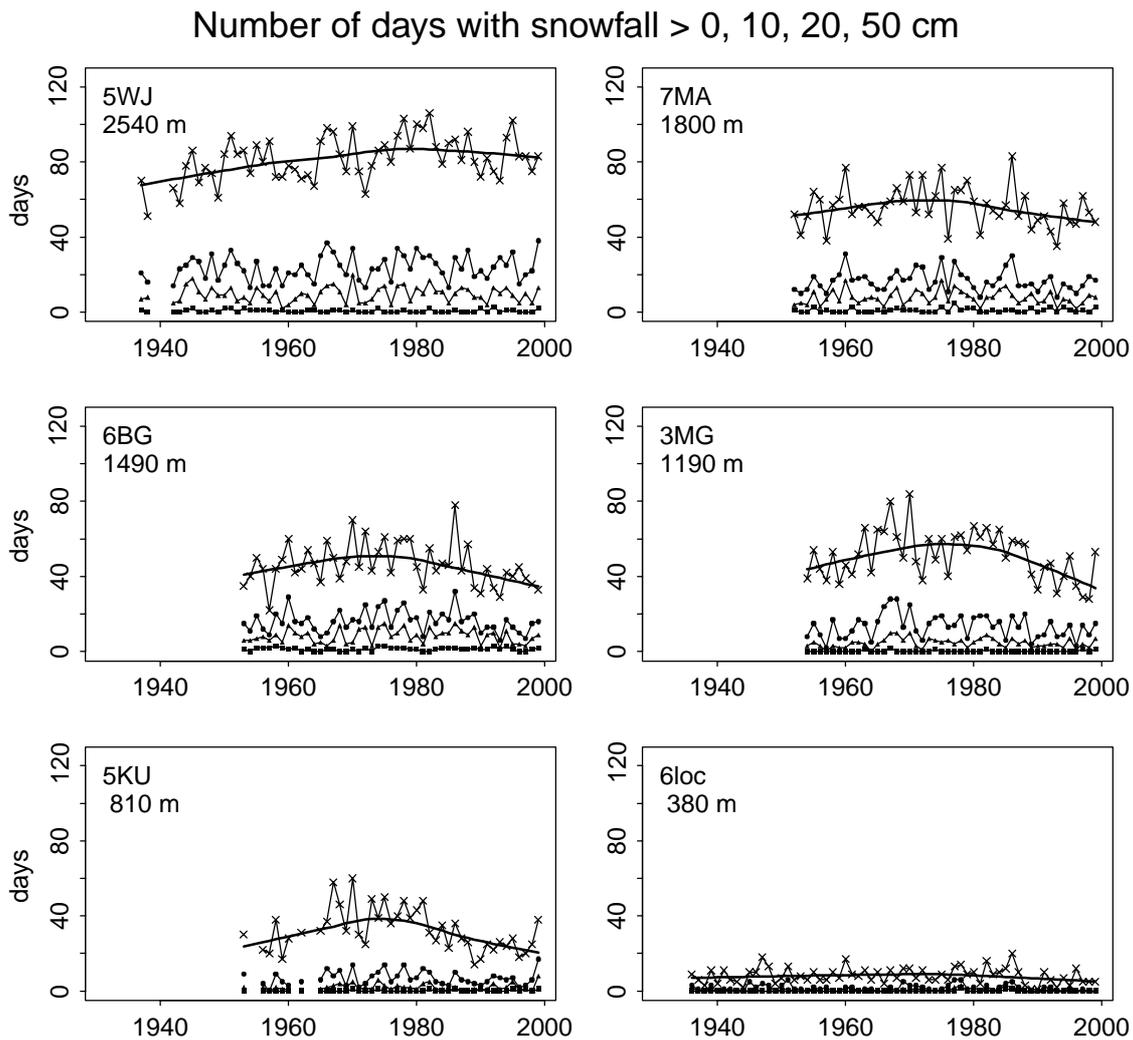
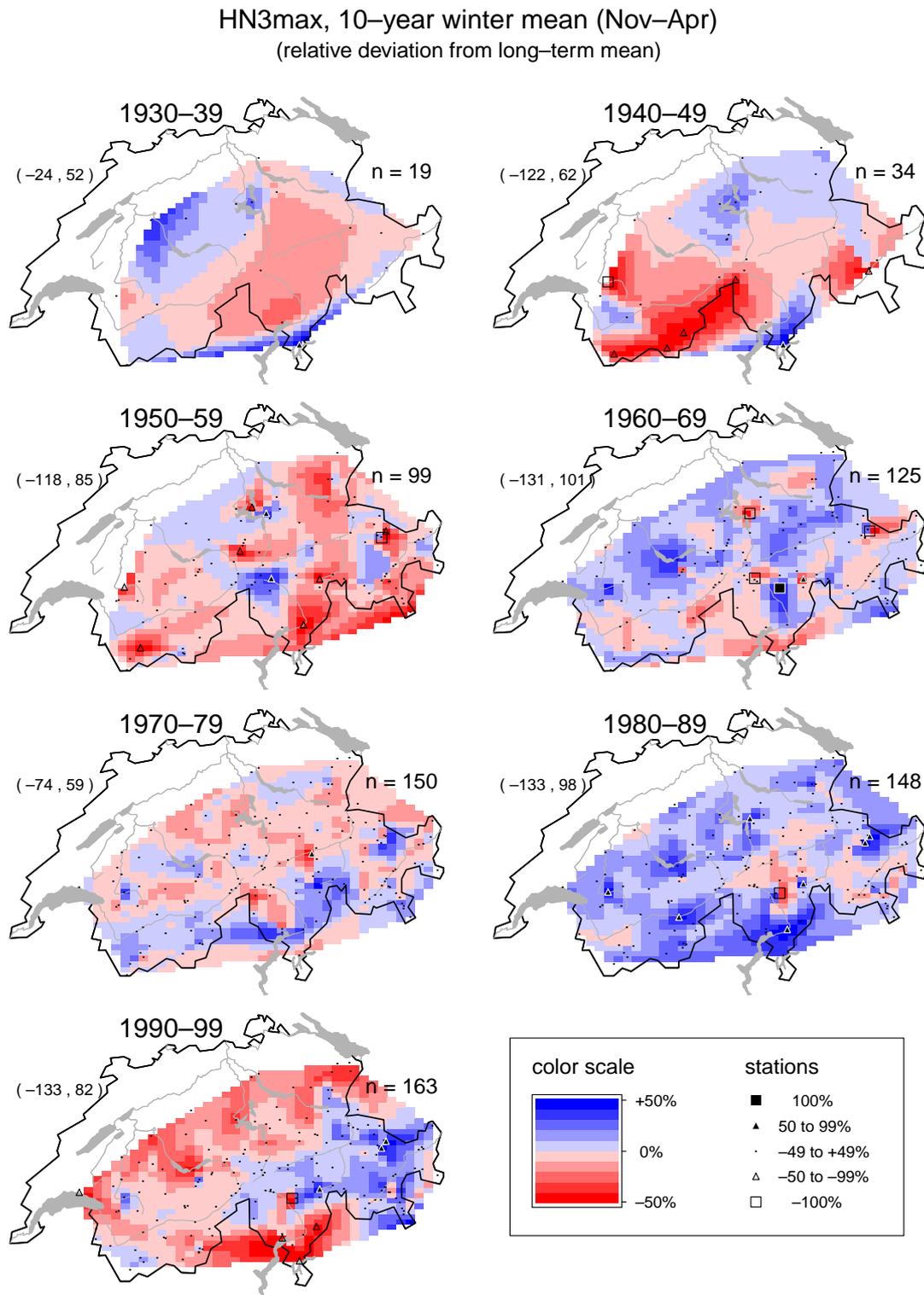


Figure 2.24: Number of days with snowfall > 0, 10, 20 and 50 cm during the last 50 – 60 years for six exemplary stations at different altitudes: Weissfluhjoch (2540 m, 5WJ), Maloja (1800 m, 7MA), Bosco/Gurin (1490 m, 6BG), St. Margrethenberg (1190 m, 3MG), Küblis (810 m, 5KU) and Locarno (380 m, 6loc). For  $HN > 0$  cm annual values (x) and lowess-smoothed long-term trends are drawn. For other thresholds only the annual values are shown:  $HN > 10$  cm (●),  $HN > 20$  cm (▲) and  $HN > 50$  cm (■).

annual  $HN3$ -maxima averaged over a decade show much more variability on a smaller scale and the range of possible extremes is considerably larger (Figure 2.25). It is hard to find decades with particularly high or low  $HN3$ -maxima, but — as for  $HS$ -mean — the 1980s were largely above average and the 90s rather below. However, the central and eastern areas received notably above average heavy snowfalls throughout the 90s. Looking at individual winters confirms the pronounced small-scale variability and points up that there are hardly any winters with throughout high or low  $HN3$ -maxima. Hardly any changes can be seen in the long-term development, neither for the whole Swiss Alps nor for single regions. However, looking at different altitude zones reveals



*Figure 2.25:* Relative HN3max-deviation (in %) of 10-year winter means (Nov–Apr) compared to the long-term mean. Dots show the availability of stations for interpolation; triangles and squares exceed the limits of the color scale (-50 to +50%). The numbers in brackets to the left of each plot give the data range and  $n$  is the number of stations.

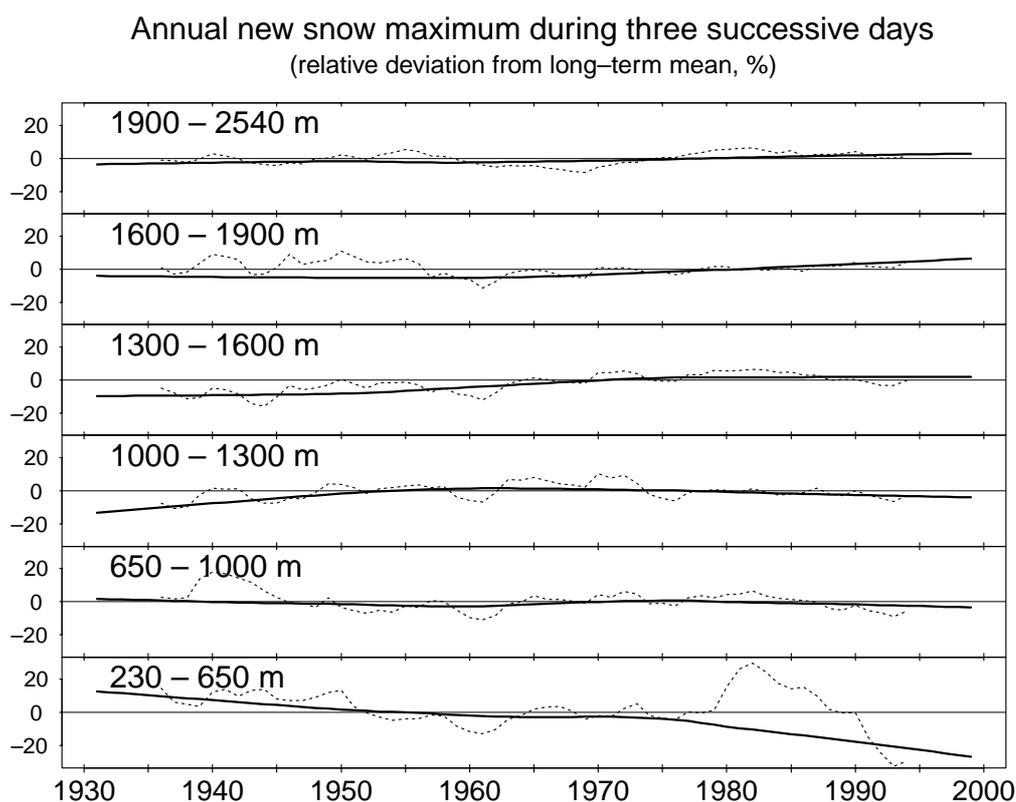


Figure 2.26: The same as Figure 2.23, but for the annual new snow maximum during three successive days (HN3max).

that stations above 1300 m a.s.l. show a very weak rising trend, while stations below that slightly tend to fall. Only the very low foreland stations (< 650 m a.s.l.) show a marked drop since the early 1980s (Figure 2.26).

## 2.5 Discussion

The mean snow depth, the duration of continuous snow cover and the number of snowfall days in the Swiss Alps all show very similar trends during the observation period of 1931 – 1999: a gradual increase until the early 1980s — with insignificant interruptions during the late 1950s and early 1970s — followed by a statistically significant decrease towards the end of the century (cf. Figure 2.14a). Regional and altitudinal variations are large; high altitudes show only slight changes and the trends become more pronounced at mid and low altitudes. The southern part of the Alps often has different conditions at a time than the north. Shorter snow duration is mainly caused by earlier snow melting in spring than by later first snowfalls in autumn.

The beginning of the availability of nationwide digitalized snow data (since 1931) falls into an era of low-snow winters. This is confirmed by time series of the few stations dating back into the 19th century (Brand, 1991; Schüepp, 1995; Schneebeli et al., 1998). Thus, the post-1930 increase was first of all a return to an average level, but then the 1960s and early 1980s obviously reached very high amounts of snow even compared to the generally snowy period around the turn of the 19th century. Towards the end of the 20th century, a low level was attained as never reached before during this century. The 1990s fall significantly below the long-term average of 1931 – 1999. However, only the 1960s and 1980s are significantly higher (on a 95%-confidence level) than the 1990s. The question remains whether the decreasing trend will continue under the influence of climate warming or the cyclic up and down goes on as before. The latest development does not necessarily point into the direction of a continuous ongoing downward trend, at least not at medium and high elevations. North of the Alps 1999 was a clear high-snow winter, even at low altitudes, and a preliminary estimate of 2000 and 2001 indicates that these winters were at least average (2001 with excessive snow amounts south of the Alps). The outlined snow trends during the 20th century can be well comprehended within the scope of the general climatic development for this period, as discussed by Wanner et al. (2000, p. 151–160).

Despite undoubtedly increasing winter temperatures Fliri (1992, I/159) could not detect systematic long-term trends analysing up to 100 years long snow series from Tyrol (*Austria*). However, data were analysed until 1991, when the strong and persistent downward trend could not be seen yet. For Northern Tyrol variations in the order of 10 – 20 years are characteristic with peaks in 1905, 1923, 1943, 1951, 1966 and 1981. This well matches the snowy periods found in Switzerland. Jaagus (1997) presents similar results for the snow duration in *Estonia*, but starting in 1892 he found a decreasing linear trend of 1.5 days per decade during the entire period until 1995. The Estonian time series point up three snowy decades until about 1925 followed by a marked drop until the mid 1930s. Then begins a persistent recovery of the snow duration until 1970, however, interrupted by two major set-backs in the late 1940s and early 1960s. After a lean period during the mid 1970s it climbs again to high values until dropping from the mid 1980s to low levels even undercutting the poor 1930s. The 107-year long series of Davos (cf. Figure 2.5a, snow depth) points to a very similar centennial pattern for Switzerland. At first sight this seems to stand in contrast to the findings of Ye (2001), who announces an increase in snow season length across the *former Soviet territory* during 1937 – 1994. However, Ye applies linear regression through the entire data period resulting in an overall positive slope, but in fact all of the four presented examples reveal a decreasing trend during the last two decades. Typical

are strong annual variations and a cyclic succession of periods with short and long winters. As for Switzerland the years from the early 1960s until the early 1980s were generally snowy winters.

Again a similar general pattern is found in *North America*. According to Hughes and Robinson (1996) the snow cover time series in the Great Plains begin 1910 on a moderate level followed by a marked decrease until the early 1930s. Then a persistent increase with the usual short set-backs continues until 1980, decreasing again until 1993 (end of data). Brown and Goodison (1996) analysed snow cover trends for various regions of southern Canada from 1915 – 1992. Whereas the Western Prairie and West Coast region closely follow the line of the Great Plains — with the decrease beginning in the early 1970s already — for the southern Ontario, Québec and Maritimes regions no obvious trends can be found. However, a striking feature for the Maritimes region is a rapid reduction in snow cover that occurred during the 1940s and the Ontario and Québec region shows at least in spring a marked decrease since 1970. Leathers and Luff (1997) conclude for the Northeast United States insignificant variations around a consistent mean value, but no long-term trend of snow cover duration for the data period 1949 – 1988. However, the annual data show a few low-snow winters in the beginning and towards the end of the observation period, indicating that the analysed time series just start at the end of the general upward trend since 1930 and terminate just after the onset of the strong downward trend since the mid 1980s. This demonstrates that depending on the time window of the analysed data, trends — especially linear trends through the entire data period — can stimulate misleading interpretations. Frei et al. (1999) show that also North American winter snow *extent* (snow covered area) tended to increase from the 1930s up to about 1980, followed by a subsequent decrease during the 1980s. Thereby the decrease in spring snow extent was stronger, which stands in agreement with results of Brown (1997), who also finds indications of decreasing spring snow extent across *Eurasia*.

This suggests that throughout the temperate and subpolar northern hemisphere a similar general pattern of temporal snow variations occurred during the 20th century. However, two long-term stations from *Japan*, Nagaoka (100 m a.s.l., 1905 – 1994, Nakamura and Shimizu, 1996) and nearby Tohkamachi (200 m a.s.l., 1918 – 1998, K. Izumi, pers. comm., July 1998), reveal a partly different picture with obvious parallels though: 1945 was an exceptionally snowy winter, the 1950s were rather lean (except the early 50s in Switzerland), the 1960s until the early 1980s (in Japan until the mid 1980s) snowy again and finally a clear decrease towards the end of the century. Less good correlated is the period prior to 1940.

*Table 2.5:* Top ten winters between 1931 and 1999 with the heaviest snowfall events averaged over the entire Swiss Alps, expressed by the relative deviation (in %) of the annual HN3-maxima from the long-term mean. The number of stations and the standard deviation are indicators for the reliability and variance of the data. The plus signs indicate the degree of above normal avalanche activity: slightly (+), strongly (++), severely (+++) (after Schneebeli et al., 1998).

<i>Winter</i>	<i>No. of stat.</i>	<i>% of mean</i>	<i>St. dev. (%)</i>	<i>Avalanches</i>
1931	17	39	87	++
1945	25	35	62	++
1968	103	34	45	++
1986	108	33	60	+
1999	92	32	38	+++
1967	101	27	43	+
1951	40	26	68	+++
1955	70	22	43	
1975	116	21	49	+++
1995	104	20	40	+

Somewhat different is the situation for *heavy snowfall events*. In the Swiss Alps there is virtually no long-term trend visible. This supports the thesis set up by Schneebeli et al. (1998) that no trend can be found for heavy snowfalls causing direct-action avalanches. On the other hand, winters with high HN3-maxima clearly correlate with an enhanced avalanche activity (Table 2.5). However, at elevations above 1300 m a.s.l. a very weak increasing trend persists towards heavier snowfalls since the 1960s and only low altitudes below 650 m a.s.l. show a marked drop since the early 1980s, indicating that heavy winter precipitation to an increasing degree falls in form of rain instead of snow. Thus, in the mountain regions problems encountered with heavy snowfalls such as disastrous avalanches, blocked mountain roads or ski field closures remained on a similar level throughout the observation period and it is not foreseeable that this will change much in the near future.

The question remains how these findings for snow trends match observed precipitation trends. Widmann and Schär (1997) analysed 113 continuously operating rain-gauge sites across Switzerland for the period of 1901 – 1990 and found a statistically significant wintertime increase in precipitation by up to 30% per 100 years in the western and northern regions. In most parts of southeastern Switzerland winter precipitation increased as well but by a smaller rate and at a slightly lower significance level. Also for the 30-year period of 1961 – 1990 (304 sites) precipitation increased in

most regions and all seasons except in summer. *It seems to be a contradiction that winter precipitation increases while snow depth and duration decrease.* One explanation may be that in a warmer temperature regime even in winter it rains more often up to high altitudes or snowfall is wetter than before. If so, the snow cover will get more compressed resulting in smaller snow depths but increased water equivalents — at least at medium and high altitudes. At low altitudes winter rain may completely melt an existing snow cover and even at mid altitudes rain can penetrate a dry snow cover and directly proceed to the runoff, without increasing the water equivalent (Rohrer, 1992, p. 79). However, trends of the annual maximum water equivalent based on 27 SLF long-term stations with more than 30 years data show no increase. Quite the reverse all but two stations reveal a decreasing tendency since the 1980s, largely parallel to the decreasing snow depth and snow duration. The only exceptions are Weissfluhjoch (2540 m a.s.l.) and Büschalp (1960 m a.s.l.), two high-altitude stations near Davos, with no obvious change during the last 63 and 53 years, respectively. Sheet 3.4 of the Hydrological Atlas of Switzerland (LHG, 1992) confirms the decreasing water equivalent — except at high altitudes — also for monthly dates from 1 January to 1 May. Regarding high altitudes Rohrer (1992, p. 58–68) pinpoints for Weissfluhjoch the immense year-to-year deviations from the long-term mean (reaching up to four standard deviations in 1975) and can not find trends comparing the two-weekly fixed dates. Even the 85-year long reconstructed (Müller and Kappenberger, 1991) and updated (Herren et al., 2001, p. 41–42) water equivalent series from two sites on the Clariden Glacier on 2700 and 2900 m a.s.l., are surprisingly constant during the entire period. Thus, the opposing precipitation and snow trends cannot be explained by a compensation in the snow water equivalent; another approach for a satisfactory explanation must be found. Perhaps it is simply the fact that the winter season with snow on the ground becomes shorter — especially during the transitional period in early and late winter it rains more instead it snows — what is particularly true at low elevations. At high altitudes increased precipitation correlate with a weak positive trend to heavier snowfall events (HN3max) and also the number of days with new snowfall > 50 cm (dhn50) shows slightly higher values since recently. Finally, the strongest precipitation increase was found in NW-Switzerland, a rather low-lying area with usually more rain than snow in winter, while the mountainous regions showed less obvious trends. Pfister (1999, p. 58–61) determines an increase in winter precipitation during the last century on the Swiss Plateau (north of the Alps), but cannot see any changes for the Alps itself.

## 2.6 Conclusions

Snow data reveal remarkably large spatial and temporal variability, even in a comparatively small area such as the Swiss Alps. Year-to-year variations far outreach subtle long-term changes, which in fact exist and are most pronounced at low elevations. Whereas high-altitude stations (above 2000 m a.s.l.) until now show hardly any signs towards a climate with less snow, the lower we get the more notable become significant snow deficiencies since the late 1980s. The 1990s were by far the least snowy decade since 1930 and on the Swiss Plateau 1988 – 1997 was the decade with the shortest snow cover duration of the past 315 years (Pfister, 1999, p. 199). Sporadic warm low-snow winters can be found throughout the last few centuries, but never did they appear in a continuous sequence of 11 years such as from 1988 to 1998 (Pfister, 1999, p. 200). Whereas the latest IPCC assessment report (2001) predicts a further temperature rise and snow depletion for the entire Northern Hemisphere, Wanner et al. (2000, p. 161–236) point out the difficulties encountered in elaborating accurate forecasts of the future climate development in the Alpine region. Additional to a multitude of temporally and spatially varying factors and their complex interactions, the longer the more human-influenced impacts on the natural climate system have to be considered. However, the North Atlantic Oscillation (NAO) is of decisive relevance for the climate system in the Alps (Wanner et al., 2000, p. 38–49). The persistent period of negative NAO indices from 1950 – 1974, with mainly cold and snowy winters storing large water reserves in the snowpack, served as a planning basis for many ski fields and hydro-power schemes. From 1974 – 1995 the NAO index turned into an extremely positive mode resulting in warm winters and temperature records in the 1990s. It was the longest observed period (since 1864) with such strong, persistent positive indices and had dramatic consequences for many low-elevated ski resorts and the related tourism and leisure time industry. The latest development since 1997 indicates another reversal of the trend towards a more negative NAO mode with colder and snowier winters again (Wanner et al., 2000, p. 239; Pfister, 1999, p. 55–56). 1999 was a clear high-snow winter on the North Slope of the Alps and 2001 on the South Slope.

The forthcoming years and decades will point the direction, whether we will veer toward an excessively warm greenhouse climate with less and less snow or the usual climate variability will proceed on as since hundreds of years with more or less pronounced anomalies. It must be stressed that at least during the past 70 years snow cover fluctuations were always most noticeable at low elevations. The nearly entire

absence of snow at low elevations during most of the 1990s is exceptional, but still remains within the bounds of natural variability. Unfortunately we do not have reliable snow records of high-altitude stations (above 2000 m a.s.l.) prior to 1930. Although three stations with up to 150 years undigitalized data exist, their position on an isolated mountain summit (Säntis, 2500 m a.s.l.) and on major passes (Gd-St-Bernard, 2480 m; Gotthard, 2100 m a.s.l.) must be considered heavily influenced by wind and snow drift. However, Schüepp (1995; after Ambühl, 1990) finds on Gd-St-Bernard a distinct minimum of the snow cover duration during the 1860s, followed by a second minimum around 1940, but no clear trend. Unfortunately the analysed series ends 1985, just before the presumed decline during the 1990s.

Evaluating old station series for long-term trends always bears problems concerning data quality and homogeneity. Utmost care must be taken elaborating the station history, since different observation techniques, shifts of the measuring plot or altered surroundings (grown trees, new buildings) can heavily influence the snow accumulation. Homogeneous long-term data series are invaluable for accurate climate trend analyses — actually they are indispensable. However, a serious concern is the world-wide decline of observational networks (IPCC, 2001). Also in Switzerland the snow observation network has passed its maximum extent in the 1970s and since then is on the decline. Manned high-altitude snow observation stations are generally rare and thus (winter) precipitation in the high mountains is still quite unexplored. Not much is known indeed of the snow distribution in an altitude zone increasingly important for many economical and social issues such as winter tourism, water management and natural hazard mitigation (e.g., evaluation of avalanche defence structures). Since hardly any direct snow observations exist, usually the values from lower stations are extrapolated into the high mountain area without any possibilities for direct confirmation; this of course bears considerable uncertainties. A promising endeavour in this matter is the increasing set up of automatic weather stations (including snow depth sensors) at altitudes between 2000 and 3000 m a.s.l. since the early 1990s (ENET- and IMIS-stations). However, attention should be paid to the following issues: 1) For the sake of continuous and homogeneous long-term series, traditional manned stations should not be closed in favour of automatic stations at new high-altitude sites. 2) Whenever manual observations are replaced by automatic sensors, the new sensors should be installed exactly at the same location of the old snow stake. 3) Traditional snow observations of manned SLF-stations (one value daily) are regularly manually quality-checked in order to assure that reliable data flows into the database. For half-hourly data of automatic stations new possibilities open up for digital filtering to screen erroneous data. 4) Whereas at manned stations HN is determined as the height of new

snow on a daily cleaned board, automatic stations cannot directly measure new snow. HN has to be calculated with snowpack models resulting in a certain difference compared to the hand measurement (possible model errors are not identical to observation errors). However, comparisons between hand measurements and model runs have been proven to be highly correlated in most cases (Lehning et al., submitted).

In order to monitor subtle climatic changes, such as snow trends strongly variable in space and altitude, a dense network of quality-checked snow data is necessary. It is urgently encouraged that forthcoming optimizations of the various snow observation networks must aspire to achieve and maintain a superior set of snow stations, both representative in space and altitude. We believe that the considerable expenses connected to that are justified, knowing of the great commercial significance of the resource snow — today and in future.

### **Additional material**

Additional illustrations are available at <http://www.slf.ch/research/snowtrends>.

### **Acknowledgements**

We would like to thank the Swiss Meteorological Institute for providing access to their climate database and the Rhaetian Railway for regularly delivering their snow depth data to our institute.



## Chapter 3

# A Probabilistic Model Based on the Spatial Extent and Frequency of Heavy Snowfall Events

*Manuscript:*

*Latenser, M. and Schneebeli, M.: A probabilistic model based on the spatial extent and frequency of heavy snowfall events used for the evaluation of the Swiss snow station networks. Submitted to Journal of Applied Meteorology.*

### **Abstract**

Daily new snow measurements are most important for avalanche forecasting and tourism. In Switzerland new snow is measured at several different snow station networks, each with a spatially variable station density. Thus, individual station networks as well as combinations of networks result in spatially inhomogeneous information of new snow events. The goal of this study is to evaluate how well heavy snowfall events can be captured by the existing snow station networks. For this purpose we developed a probabilistic model based on the frequency and spatial extent of areas covered by heavy snowfalls and applied it to the observational networks. This gives the station managing authorities a quantitative measure to locate deficiency or surplus areas and to optimize their networks. In order to obtain a spatially continuous snowfall capture probability of at least 80%, ideal networks should have a triangular spacing of about 15 km. Spacings of 20 km result in only 50% guaranteed capture probability, which means we will miss at least half of all local snowfall peaks in areas with a sparse station coverage and thus avalanche forecasts will locally underestimate the situation in at least half of all cases. The Swiss operational snow station network (a combination of several partial networks) widely fulfills the optimal requirements, actually it is in many places rather too dense. However, serious deficiency areas exist all along the national border and in the south/south-east.

### 3.1 Introduction

One of the most important parameters for the evaluation of the avalanche hazard is daily new snow (McClung and Schaerer, 1993). Consequently the quality of the hazard estimation largely depends on accurate new snow forecasts and the timely availability of measured new snow data. However, new snow forecasts do not have a very high spatial resolution (Majewski, 1991) contributing to major uncertainties for avalanche forecasting on a regional and local scale. Therefore a sufficiently dense network of stations measuring new snow is indispensable for a high-resolution real-time avalanche hazard estimation.

On a complex mountain topography such as the Swiss Alps an adequate distribution of snow stations is necessary also for many other applications relying on highly resolved snow data. Examples are: snow climatological mapping and trend analyses (Witmer et al., 1986; Chapter 2 of this work), determination of snow loads for engineering purposes (SIA, 1989), knowledge of snow distribution for resort management and touristic information (Abegg, 1996), calculation of snow reserves for hydro-electric power production (Ehrler, 1998), etc. Thus, the determination of an ideal network density for snow stations reaches far beyond avalanche warning purposes.

Both the Swiss Meteorological Institute (SMA) and the Swiss Federal Institute for Snow and Avalanche Research (SLF) maintain several networks recording daily new snowfall. They consist of either manually or automatically recording stations. Whereas the amount of new snow at manual stations is every morning measured by an observer, the automatic stations only determine the total snow depth (usually in hourly intervals) and the daily new snow has to be calculated with real-time snowpack settling models (Lehning, submitted). Depending on the application, data from different networks can be selected. However, it has to be born in mind that the first automatic stations started with operational measurements a mere 10 years ago, which excludes any analyses needing long-term data. Most manual SLF-stations report the data electronically on a daily basis to the central data server, but some stations transmit their data only once a months in form of a written table. Of course such data can not be used for operational purposes, but for retrospective climate analyses. All individual networks and some combinations are listed in Table 3.1.

Table 3.1a: List of examined snow station networks (original networks).

<i>Code</i>	<i>Stations (2001)</i>	<i>Altitude [m a.s.l.] (min...median...max)</i>	<i>Managing institution</i>	<i>Type</i>	<i>Observation</i>	<i>Reporting</i>
VG	80	1090...1595...2690	SLF	manual	daily	daily
MS	35	230...1200...2910	SLF	manual	daily	monthly
KSS	65	273.....635...2540	SMA	manual	daily	daily
IMIS	77	1610...2455...3345	SLF	automatic	hourly	hourly
ENET	11	1890...2517...3130	SMA/SLF	automatic	hourly	hourly

Table 3.1b: List of examined snow station networks (combined networks).

<i>Code</i>	<i>No. of stations (active in 2001)</i>	<i>Networks</i>	<i>Description</i>
AUT	88	IMIS + ENET	all automatic stations
MAN	135	VG + KSS	all manual operational stations (without 10 SMA-SLF-station doubles at the same location)
OPER	233	VG, KSS, IMIS + ENET	all operationally reporting stations
CLIM	268	VG, KSS, IMIS, ENET + MS	all networks together (OPER + MS) for retrospective climate analyses

The goal of this study is to evaluate how well heavy snowfall events can be captured by our existing snow station networks and to design optimized networks. Widespread heavy snowfalls are well reflected by the records of many stations, but such events are rare. Much more frequent are spatially small heavy snowfall peaks, which probably often fall through the mesh of our station network and remain unmeasured. Therefore we developed a probabilistic model based on the frequency and spatial extent of areas covered by heavy snowfalls and applied it to several different observational networks. This gives the network managing authorities a quantitative measure to locate deficiency and surplus areas in order to optimize their station networks.

Previous studies highlighting the spatial extent of precipitation areas are rare and mainly concern rain (Germann and Joss, 2001; Asquith and Famiglietti, 2000; Krzysztofowicz, 1999). However, Spreitzhofer (1999) discusses spatial characteristics of heavy snowfall events in Austria. In any case the spatial variability of precipitation is generally recognized being large and the rainfall rate at the ground is known to easily vary by a factor 10 within 2 km distance (Gabella et al., 2000).

### 3.2 Data and method

Daily new snow (HN) data from 107 manually recording snow and weather stations of the SLF- and SMA-observational networks at altitudes between 1150 and 1850 m a.s.l. were used (Figure 3.1). The elevation zone was reduced to mid altitudes in order to limit altitude effects on the snowfall distribution. Although daily new snowfall shows only weak altitudinal gradients (see Chapter 4), at low elevations it often rains in winter (instead it snows) and higher elevations are increasingly influenced by wind and other factors disturbing a homogeneous snowfall regime. Only quality-checked data were used (see Chapter 2), however, stations with missing values were not consequently eliminated, because hardly any station has throughout continuous HN-records and we would end up with a ridiculously small set of “perfect” stations.

For the 30-year period of 1969/70 – 1998/99, every winter day (180 days from 1 November to 29 April) with at least one station exceeding 30 cm of new snow was selected and used for further processing. For each of these 854 days a map with the spatial extent of  $HN > 30$  cm was drawn and the area was calculated. This was attained by applying linear interpolation within a triangulation scheme across the daily data sample on a  $5 \times 5$  km grid resolution (S-Plus functions *interp* and *image*; StatSci, 1993). Figure 3.2 demonstrates that we often get several partial areas with  $HN > 30$  cm on one day and each of this partial area was treated as an own, isolated heavy snowfall area. Obviously one snowfall event (which may spread across whole Switzerland) can have regionally and locally different snowfall intensities leading to isolated HN-peaks exceeding 30 cm. Depending on the applied interpolation algorithm and the daily station density (which may differ because of missing values), the calculated snowfall area of every single day will not perfectly meet reality. However, daily deviations are smoothed within the large data sample. Subsequently, daily areas with more than 30 cm of new snow are called *HN30-areas* and days with more than 30 cm of new snow we call *HN30-events*.

The frequency distribution (histogram) for all 1786 HN30-areas is shown in Figure 3.3a and b. The normalized cumulative sum of the histogram gives us the probability curve for the size of a HN30-event (Figure 3.3c). If the area is logarithmically transformed, the cumulative probability  $P$  of a HN30-area  $A$  is nearly linear for areas of up to  $5000 \text{ km}^2$  (Figure 3.3d):

$$P = ( \log_{10}(5000) - \log_{10}(A) ) \cdot 0.31 \quad (3.1)$$

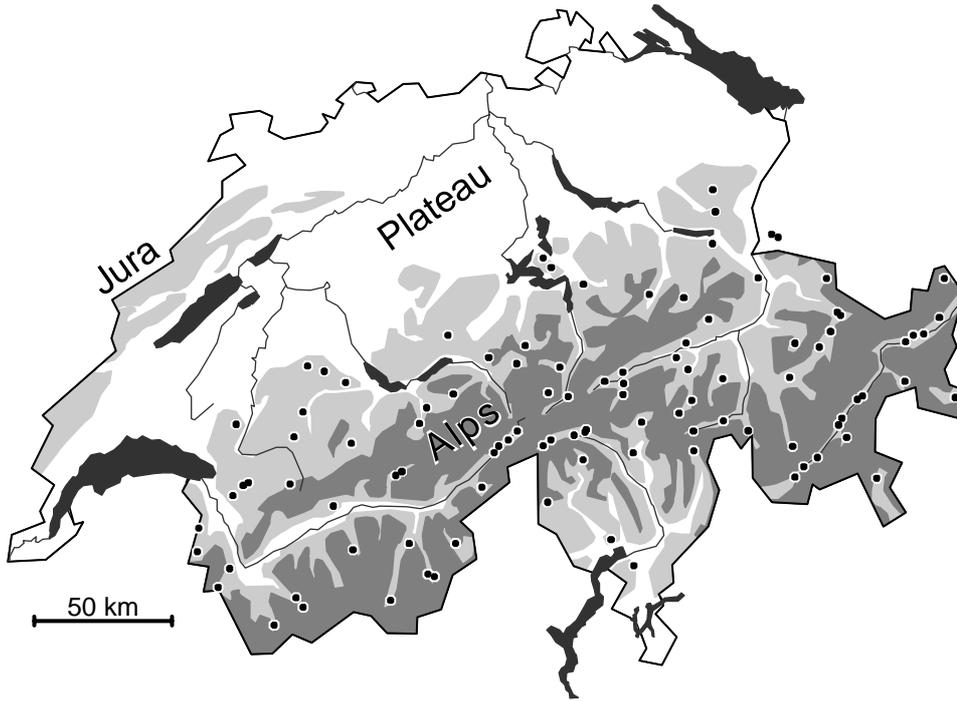


Figure 3.1: Map of Switzerland with all 107 snow stations used for the daily new snow area calculation. Grey levels indicate the topography (white: < 1000 m, light grey: 1000 – 2000 m, dark grey: > 2000 m).

Although the probability curve approaches one, for our purposes we assume that areas > 5000 km<sup>2</sup> have a cumulative probability of one. Or, the other way round, the chance that a HN30-event reaches an area greater than 5000 km<sup>2</sup> is zero. This assumption simplifies the modeling and can be justified, because in our application we are not interested in the extremely large events, but in the events with a high occurrence.

In order to evaluate the probability how good heavy snowfall events can be captured by the existing station network, the next step is to calculate the *capture probability* for such events on a 5 × 5 km grid. If we have only one station, the capture probability (CP) is highest at the station itself (CP = 1) and in its immediate surroundings. The further away we go from the station, the smaller becomes CP and after Equation 3.1

$$CP = (\log_{10}(5000) - \log_{10}(\pi r^2)) \cdot 0.31 \quad (3.2)$$

where  $r$  is the radius from the station. Assuming an isotropic probability distribution, this numerically constructed formula is only valid within a range of 1 km <  $r$  < 40 km (the circle area of 5000 km<sup>2</sup> corresponds to a radius of 39.894 km). For  $r < 1$  km CP is artificially kept at 1 and for  $r > 40$  km CP is constantly 0. That means the maximum

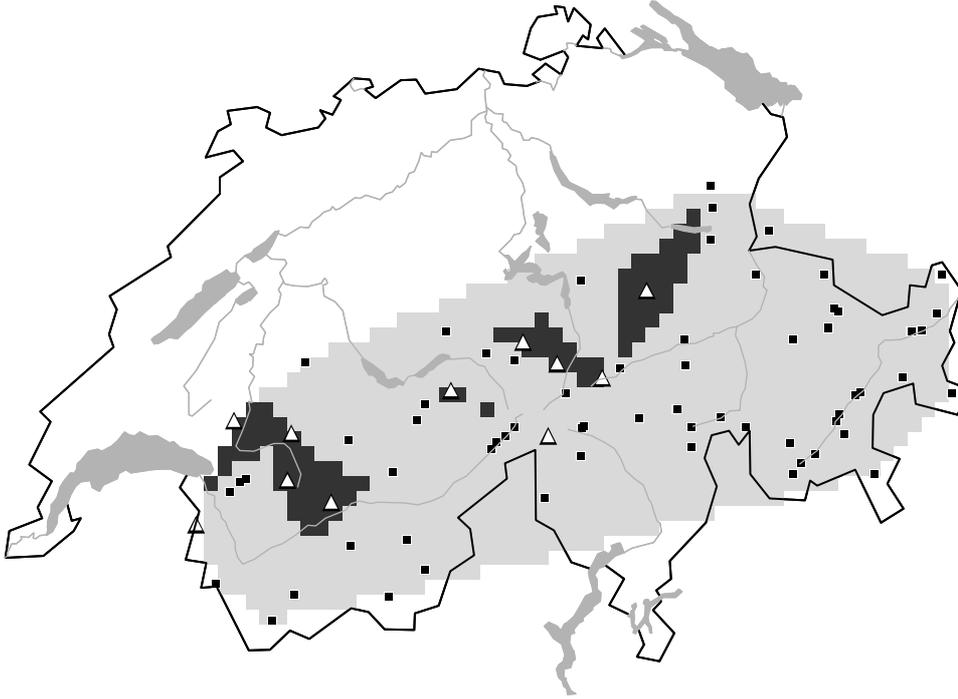


Figure 3.2: Interpolated HN30-area of an exemplary day (black areas). White triangles show stations with  $HN > 30$  cm, black dots are stations with  $HN \leq 30$  cm and the grey area encompasses the entire interpolation area.

distance up to which a HN30-event can be seen, with decreasing probability, is up to 40 km away from the station. One station influences our wanted capture probability up to a radius of 40 km from the station.

If we have two or more stations, which are further apart than 80 km, they do not interact and the capture probability for the areas around the stations can be directly calculated (Equation 3.2). In the case of several stations within 80 km, the total capture probability for areas between these stations depends on the cumulative effect of all capture probabilities together. Under the assumption that the station data is independent and randomly distributed, the total capture probability  $CP_{ind}$  for a point influenced by several stations is

$$CP_{ind} = 1 - ((1 - CP_A) \cdot (1 - CP_B) \cdot (...)) \quad (3.3)$$

where  $CP_A$  is the independent CP of station A and  $CP_B$  the independent CP of station B according to Equation 3.2. However, in reality the stations are autocorrelated. The closer they are, the higher is the autocorrelation  $\gamma$ , which depends on the distance

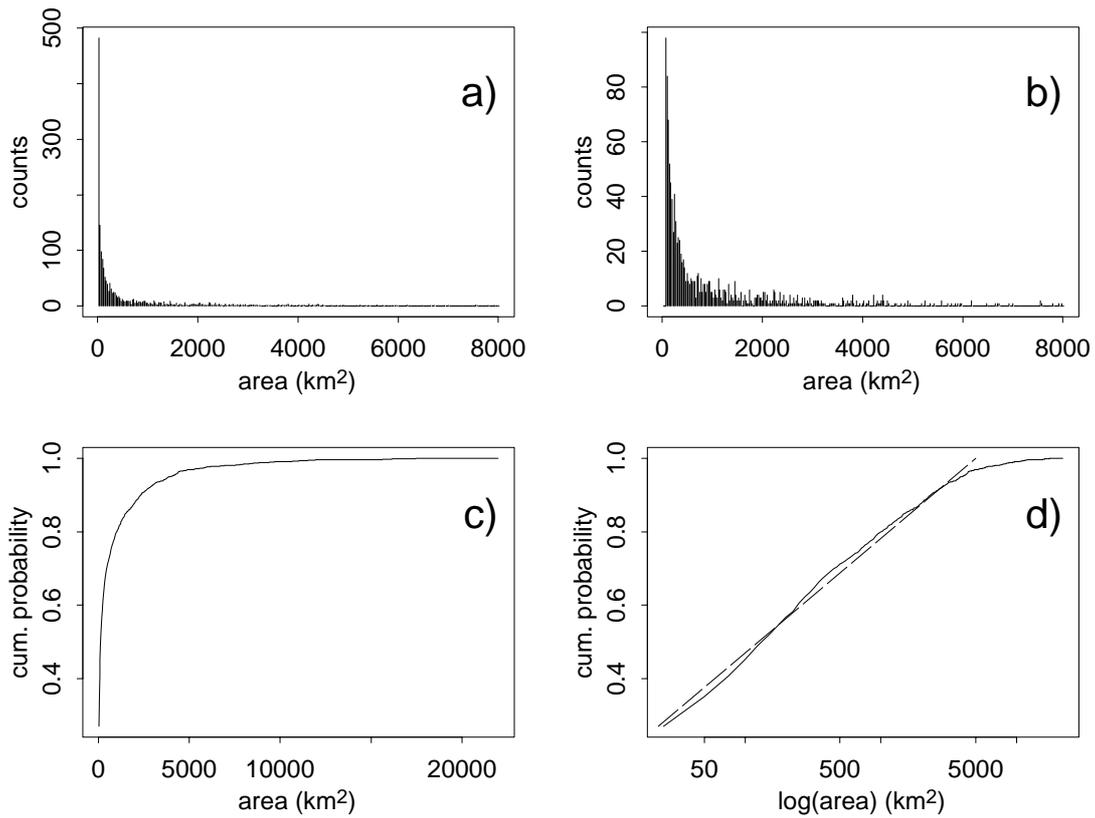


Figure 3.3: (a) Histogram of all HN30-areas in 25 km<sup>2</sup>-resolution; (b) the same histogram without the two most frequent situations (only areas > 50 km<sup>2</sup>); (c) the normalized cumulative sum (probability curve); and (d) the logarithmic probability curve including a linear approximation for areas ≤ 5000 km<sup>2</sup> (dashed line).

between the two stations.  $\gamma$  ranges from 0 (low) to 1 (high autocorrelation). Figure 3.4a illustrates the calculation of  $\gamma$ :

$$\gamma' = \int CP_{\text{ind, AB}} / \int CP_A \quad (3.4a)$$

$\int CP_{\text{ind, AB}}$  is the integrated probability of the intersection of the two influence areas of A and B after Equation 3.3 and  $\int CP_A$  is the integrated probability of the entire influence area of A after Equation 3.2. In order to get values from 0 – 1,  $\gamma$  has to be standardized with the situation when both stations fall together (distance = 0):

$$\gamma = \gamma' / \gamma'_{d=0} \quad (3.4b)$$

Figure 3.4b shows the calculated  $\gamma$  in relation to distance.

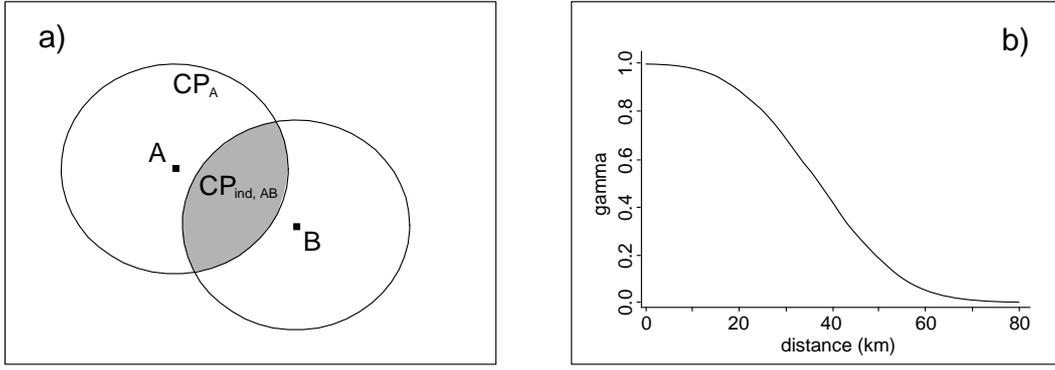


Figure 3.4: (a) Derivation of the autocorrelation  $\gamma$  (Equation 3.4a): The closer two stations, the larger is the intersection of the commonly influenced areas and the higher is  $\gamma$ ; (b) autocorrelation  $\gamma$  in relation to distance based on HN30-events.

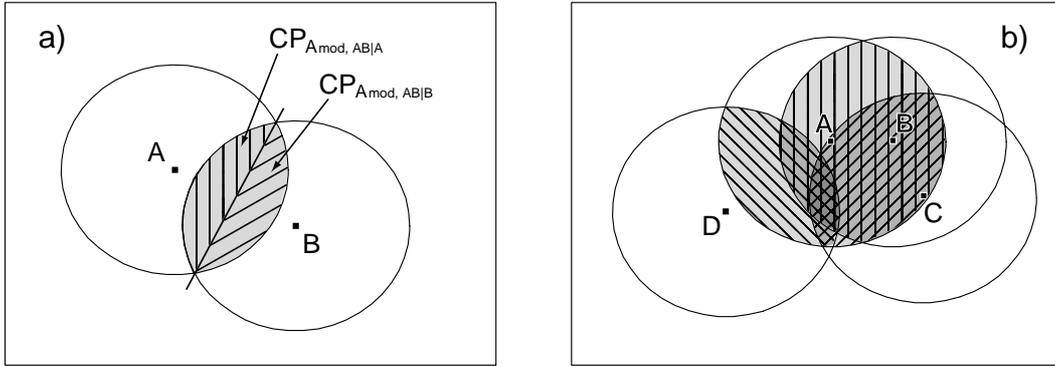


Figure 3.5: (a) Visualization of the modified capture probability between two autocorrelated stations (Equation 3.5); (b) modified capture probability of station A, stepwise considering the partial influences of B (vertical), C (right-angled) and D (left-angled hatching).

For autocorrelated stations  $CP_{ind}$  overestimates the real capture probability and we have to correct for this effect. The modified capture probability  $CP_{mod}$  between two autocorrelated stations also takes into account  $\gamma$  and is different for the two half sections of the area influenced by both stations (Figure 3.5a):

$$CP_{Amod, AB|A} = 1 - ((1 - CP_A) \cdot (1 - CP_B(1 - \gamma))) \quad (3.5a)$$

$$CP_{Amod, AB|B} = 1 - ((1 - CP_B) \cdot (1 - CP_A(1 - \gamma))) \quad (3.5b)$$

To obtain  $CP_{mod}$  on a point influenced by several stations we proceed stepwise. First we regard station A and calculate the modified capture probability together with station B (Equation 3.5). Then we use  $CP_{Amod, AB}$  as partial input for the calculation of  $CP_{Amod, ABC}$  and continue until all intersecting areas are calculated (Figure 3.5b). The modified

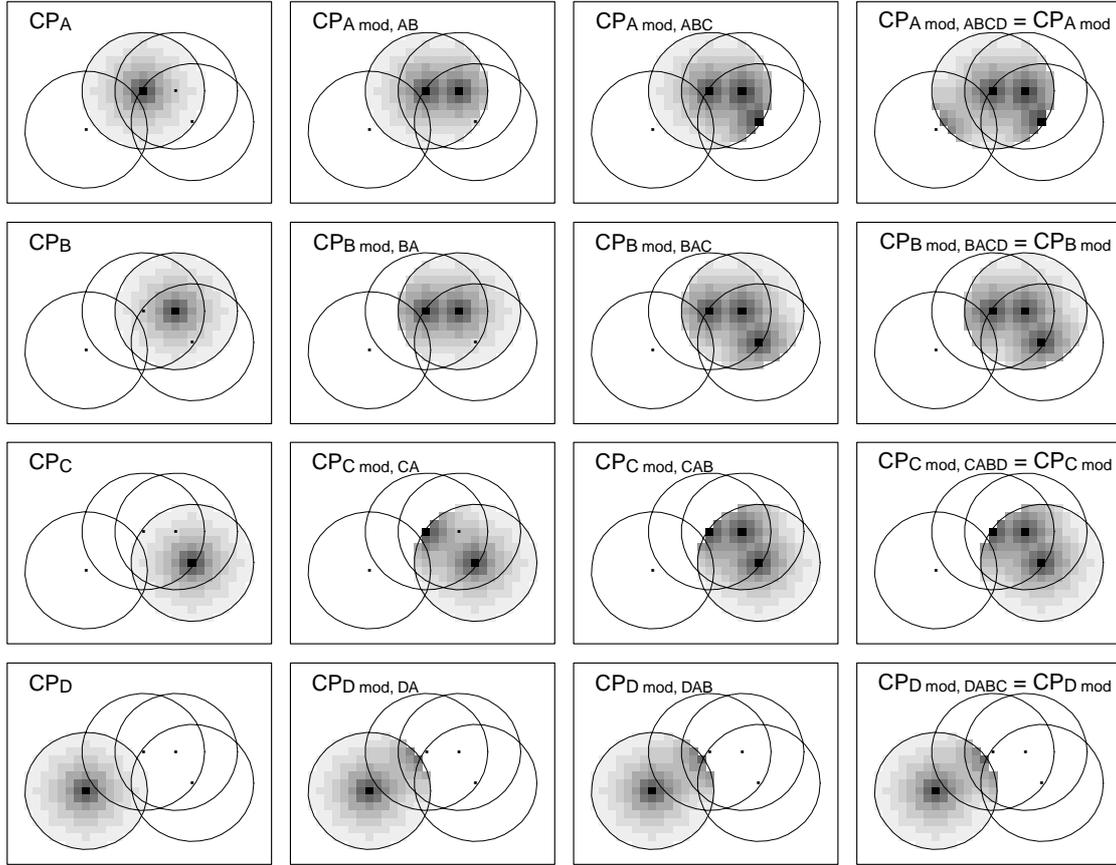


Figure 3.6: Step-by-step modification of the capture probability matrix for station A (see text for explanations).

capture probability for all stations thus considers those stations in the common interaction area. Finally we superimpose all modified capture probabilities:

$$CP_{\text{mod}} = \text{mean} ( CP_{A\text{mod}}, CP_{B\text{mod}}, \dots ) \quad (3.6)$$

The mechanism of the algorithm is visualized on a fictitious example with four stations (Figure 3.6). Each row shows the step-by-step modification of the CP-matrix for the stations A – D (cf. Figure 3.5b). The first picture of the first row shows the CP influenced only by station A. Then follow (to the right) three pictures with the modifying influence of stations B, C and D to A. The fourth and last picture of the first row is simultaneously the totally modified capture probability of station A ( $CP_{A\text{mod}}$ ) to be used in Equation 3.6. The second row shows this process for station B, the third row for C and the fourth row for D. The final superimposed result of all four modified capture probabilities is shown in Figure 3.7a. For comparison, Figure 3.7b shows the result using independent capture probabilities of non-autocorrelated stations after Equation 3.3, resulting in an overestimated CP.

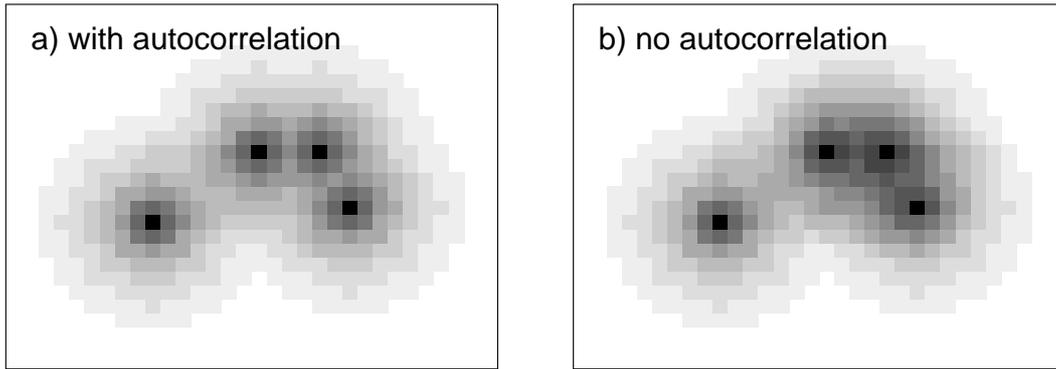


Figure 3.7: (a) Final capture probability distribution for the exemplary four autocorrelated stations of Figure 3.6; (b) the same under the assumption of independent (not autocorrelated) stations.

### 3.3 Results

The probabilistic model was applied to several snow station networks, combinations and parts of existing networks, in order to determine the effectiveness of the station density to capture heavy snowfall events. First, we discuss four network combinations (Table 3.1b) with regard to HN30-events:

- 1) **Automatic stations (AUT):** The distribution of automatic stations is fairly good throughout the high mountains resulting in capture probabilities (CP) of  $> 70\%$  in most areas. Major gaps exist in the central east (CP  $\approx 50\%$ ) and the border areas/southern valleys of the south-east (CP  $< 50\%$ ). In the mid and lower south are no stations at all (Figure 3.8a).
- 2) **Manual stations (MAN):** The manual stations are quite evenly distributed across the Swiss Alps guaranteeing a CP of at least  $50\%$ . Much higher CPs are only reached directly around stations and near isolated station conglomerates; best covered are the central regions. In the lower areas north of the Alps (Plateau, Jura) distances between stations are too large to result in high CPs. In case the automatic network fails, the manual stations guarantee at least CPs  $> 60\%$  in most Alpine regions (Figure 3.8b).
- 3) **Operational stations (OPER):** This is the maximum number of daily transmitting snow stations in Switzerland to be used for operational purposes (avalanche warning, weather forecasting, current climate information, etc.). The superposition of all individual networks results in a good coverage throughout the Alps. Nearly

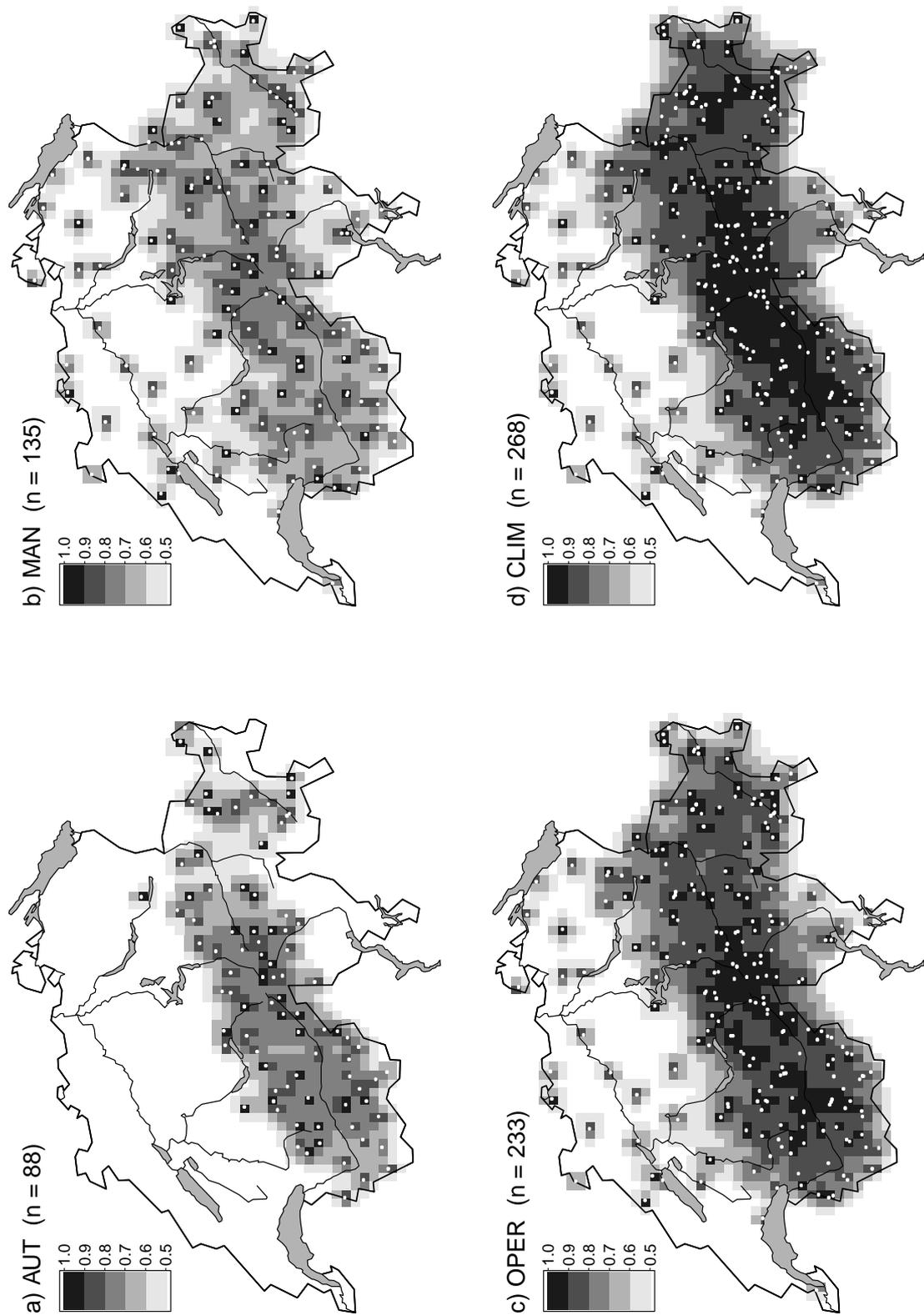


Figure 3.8: Calculated capture probability of HN30-events for four different combinations of existing snow station networks (coding after Table 3.1). White dots represent stations.

half of the area bears CPs  $> 90\%$  and most remaining areas have at least CPs  $> 80\%$ . Problematic regions with lower CPs are widespread in the south, some parts in the east and along the northern foothills. The sparse station coverage in the lower areas of the Swiss Plateau and the Jura Mountains can be coped with, since none of these areas are prone to avalanching nor heavy snowfalls in general. However, all border areas are insufficiently covered (Figure 3.8c).

- 4) **Climatological stations (CLIM):** In addition to the operational network, for retrospective climate analyses also the monthly reporting MS-stations can be used. Because of their concentration in the central and eastern/southeastern areas, the OPER-deficiencies particularly in the eastern sector can be widely closed (Figure 3.8d).

So far the analyses were based on HN30-events. However, in the same manner we can use other snowfall limits, such as HN  $> 20$  cm, HN  $> 50$  cm or HN3 (new snow sum during three days)  $> 75$  cm. Depending on the various input data we receive different probability distributions (Figure 3.9). Whereas HN20 and HN30 can be well approached by a linear function (cf. Figure 3.3d), for HN50 and HN3/75 this becomes too approximate and the numerical distribution must be fitted by a local regression model. Also the autocorrelation  $\gamma$  (cf. Figure 3.4b) must be adapted. However, the  $\gamma$ -fits for HN30, HN50 and HN3/75 are nearly identical and only HN20 shows a clear deviation (Figure 3.10). HN20-events occur on average on 47 days per year (at least one station between 1150 – 1850 m a.s.l.), HN30-events on 28 d/y, HN3/75-events on 22 d/y and HN50-events still on 9 d/y.

Applied to real networks, for HN20 a flatter probability function and a flatter  $\gamma$ -fit results in significantly higher CPs, particularly in areas with a high station density (Figure 3.11a). On the other hand, the initially steep probability function for HN50 leads to considerably reduced CPs compared to the HN30-situation (Figure 3.11b), but the effect is soon reduced with growing distance away from the stations (Figure 3.11c). HN3/75-events result in CPs between HN30 and HN50, except in the close neighbourhood of stations, where CPs very much resemble the HN30-situation (Figure 3.11d).

In order to determine the optimal station density we also run the model on artificial station grids of various spacings and calculated both the minimum and mean capture probability ( $CP_{\min}$  and  $CP_{\text{mean}}$ ) between the stations. The different grids were constructed

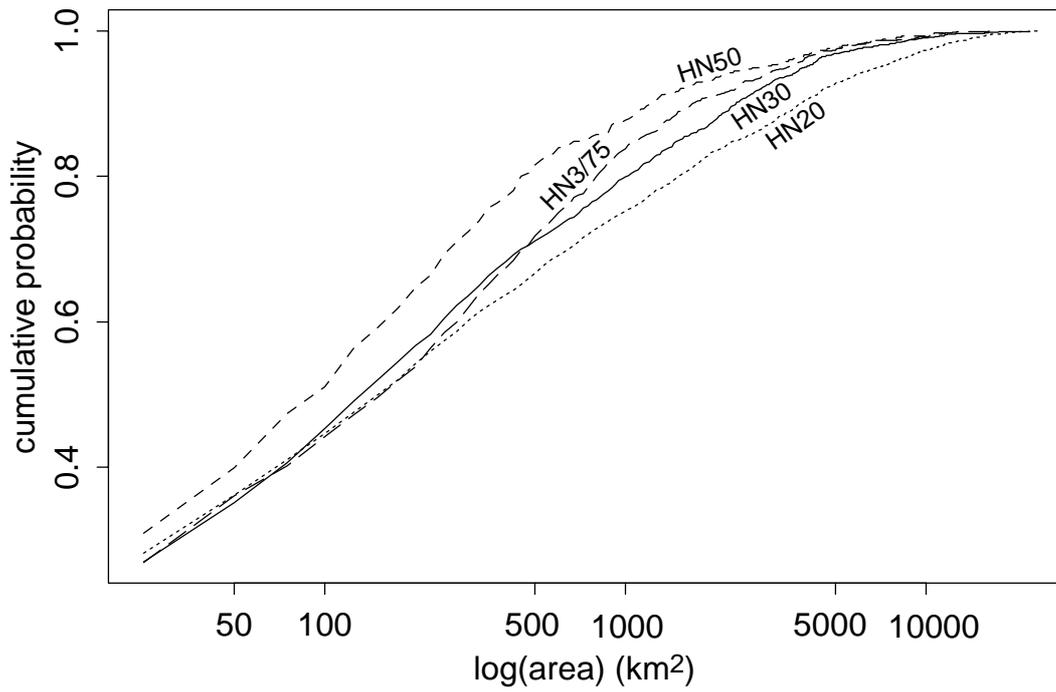


Figure 3.9: Probability distribution based on various snowfall limits: HN > 20 cm (HN20), HN > 30 cm (HN30, cf. Figure 3.3d), HN > 50 cm (HN50) and HN3 (new snow sum during three days) > 75 cm (HN3/75).

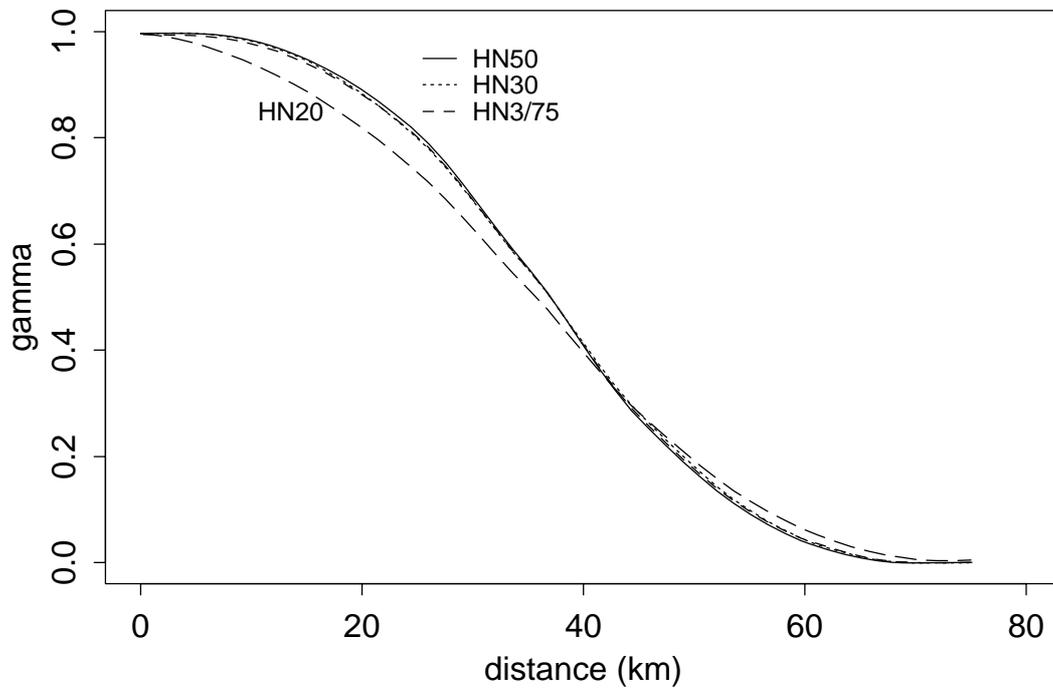


Figure 3.10: Autocorrelation  $\gamma$  in relation to distance based on the four scenarios of Figure 3.11.

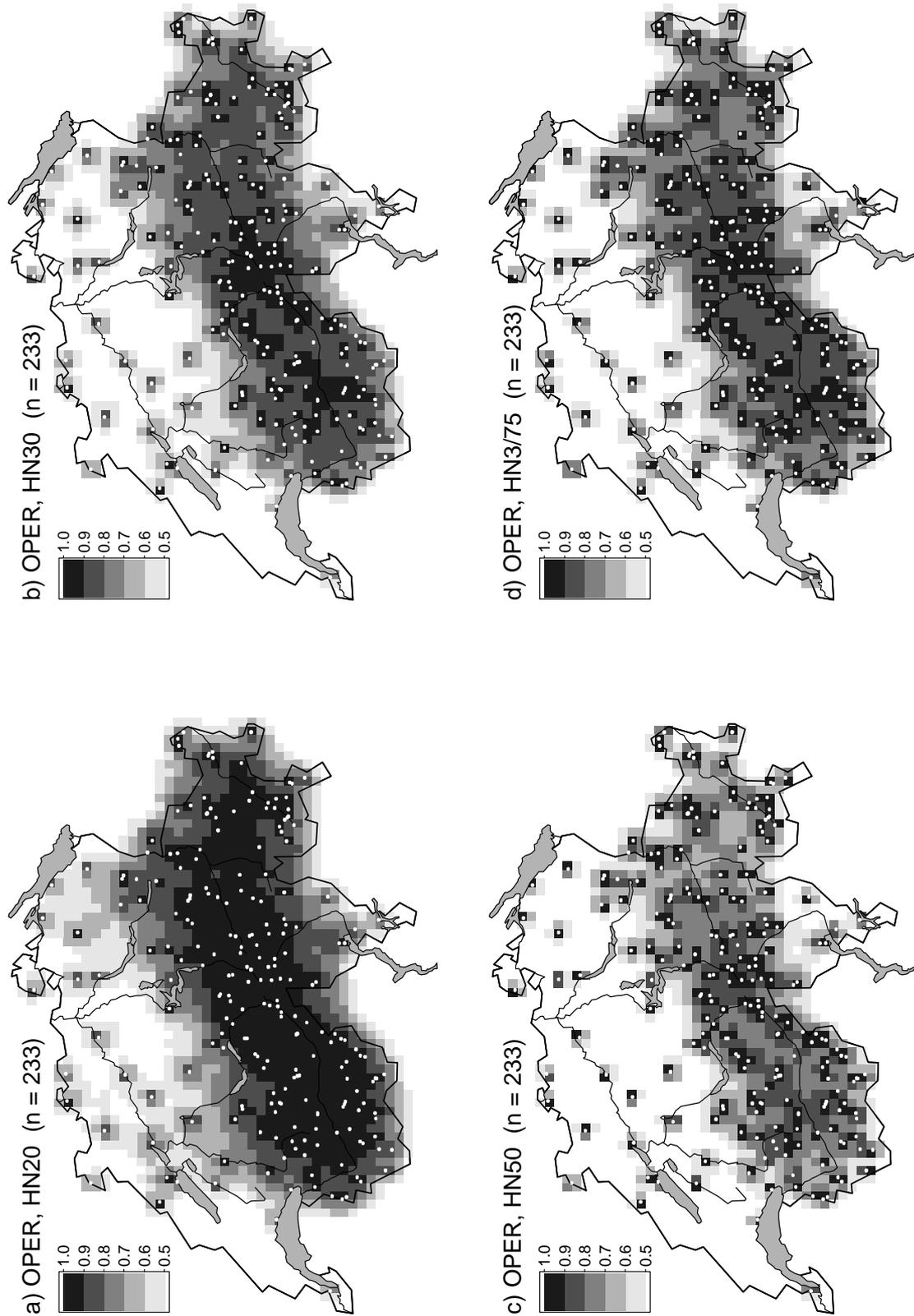
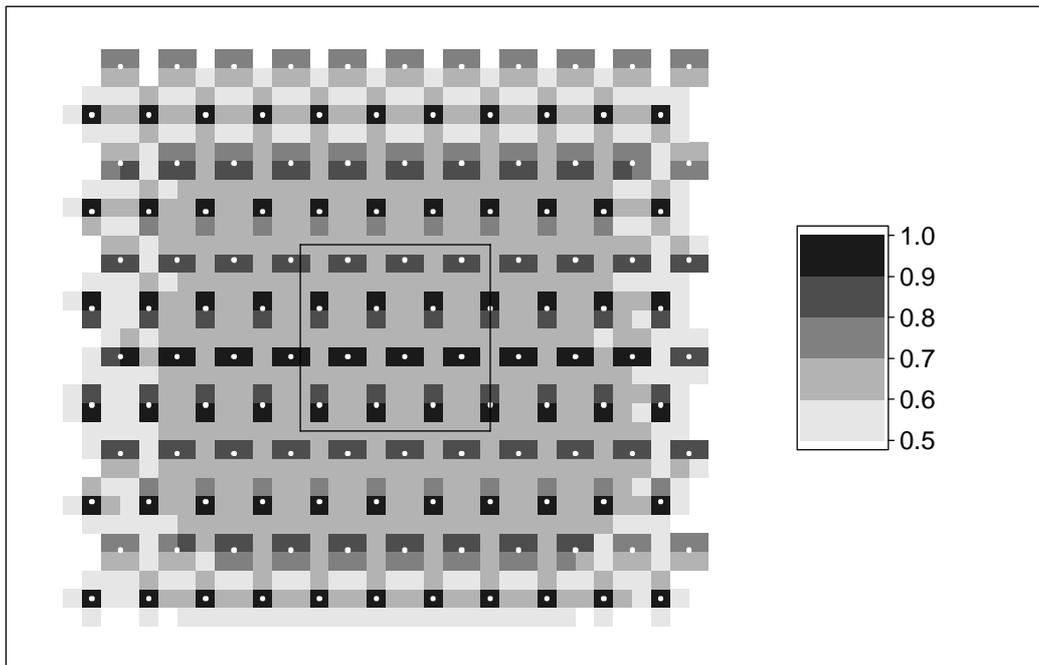


Figure 3.11: Calculated capture probability of HN20, HN30, HN50 and HN3/75 for the operational snow station network (OPER). White dots represent stations.



*Figure 3.12:* Exemplary artificial station grid with 15 km triangular spacing. Stations are located within an outer frame of  $150 \times 150$  km. The CP-distribution (here based on HN50-events) was only analysed inside the center square of  $50 \times 50$  km, where the pattern is uninfluenced by marginal effects.

by equilateral triangles with side lengths of 5 – 50 km and reaching a maximum extent of  $150 \times 150$  km. To eliminate marginal effects only the center square of  $50 \times 50$  km was used for the minimum and mean calculation (Figure 3.12). This results in a relation between station spacing and  $CP_{\min}$  ( $CP_{\text{mean}}$ ), which is different for various snowfall limits (Figure 3.13). In order to get  $CP_{\min} = 80\%$  the ideal network for HN20 should have spacings of about 16 km, for HN30 13 km, for HN50 11 km and for HN3/75 also about 13 km. The corresponding spacings for  $CP_{\text{mean}} = 80\%$  are about 1 km higher. Whereas for high CP-limits optimal spacings for  $CP_{\min}$  and  $CP_{\text{mean}}$  do not differ much, for lower CP-limits the difference between  $CP_{\min}$  and  $CP_{\text{mean}}$  increases. For a CP-limit of 50% and based on HN50-events the difference between optimal spacings for  $CP_{\min}$  and  $CP_{\text{mean}}$  amounts up to 10 km already.

Thus, the inter-station distance distribution of real networks serves as indicator for the homogeneity of a network with regard to capture heavy snowfall events. For the networks AUT, MAN, OPER and CLIM the distances were calculated using Delauney triangulation and histograms plotted (Figure 3.14). Ideal are histograms with a dominant peak around the optimal distance (13 km for HN30-events and  $CP_{\min} = 80\%$ )

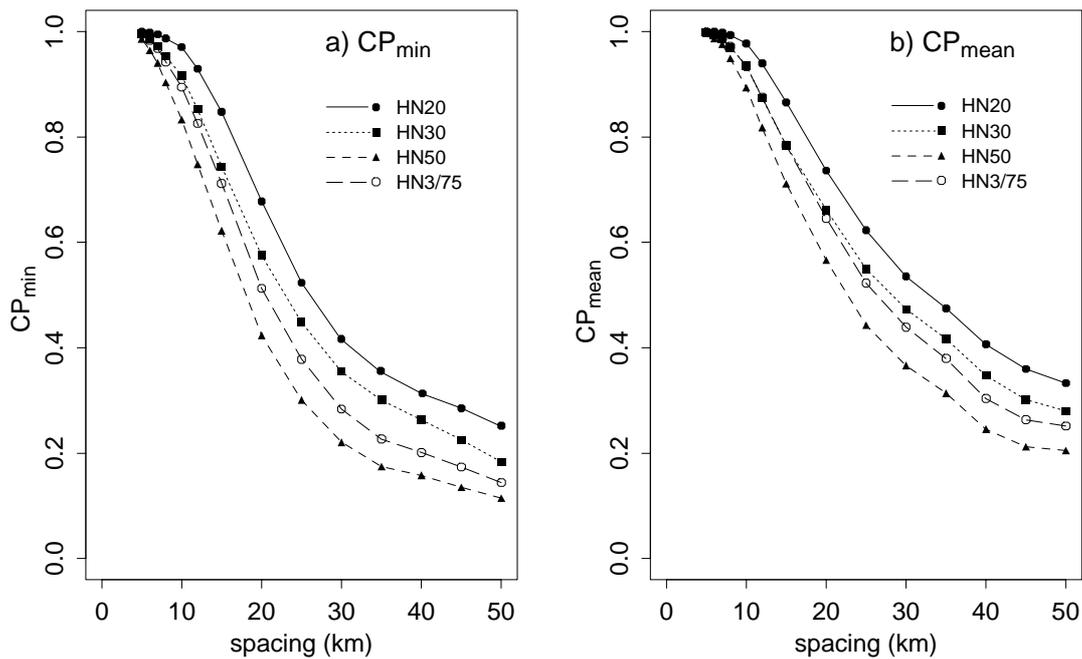


Figure 3.13: Station spacing in relation to the (a) minimum and (b) mean capture probability ( $CP_{\min}$  and  $CP_{\text{mean}}$ ) for artificial station grids, based on HN20-, HN30-, HN50- and HN3/75-events.

and strongly declining flanks to the left and right. We discuss now the quality of the four networks based on HN30-events: The automatic station network (**AUT**) widely fulfills these ideal requirements with hardly any stations within 5 km, then a marked increase up to 15 km followed by a gradual decrease towards larger distances. The only disturbance of the ideal performance is the rather gradual decrease after 20 km, which means that in some areas stations are still too far apart to guarantee throughout high CPs. However, some of the large distances are an artefact caused by the distance calculation resulting in excessively large distances along the edge of the distance polygons (Figure 3.15). The manual station network (**MAN**) has a peak near 20 km and thus is rather too coarse; also both flanks decrease too slowly. The operational station network (**OPER**) is, according to the above defined standards, in many places rather too dense (many stations within 5 km, peak at 5 – 10 km) and in other areas too sparsely covered (slowly declining right flank). For the climatological station network (**CLIM**) the tendency to too many nearby stations is even increased, whereas stations far apart are reduced.

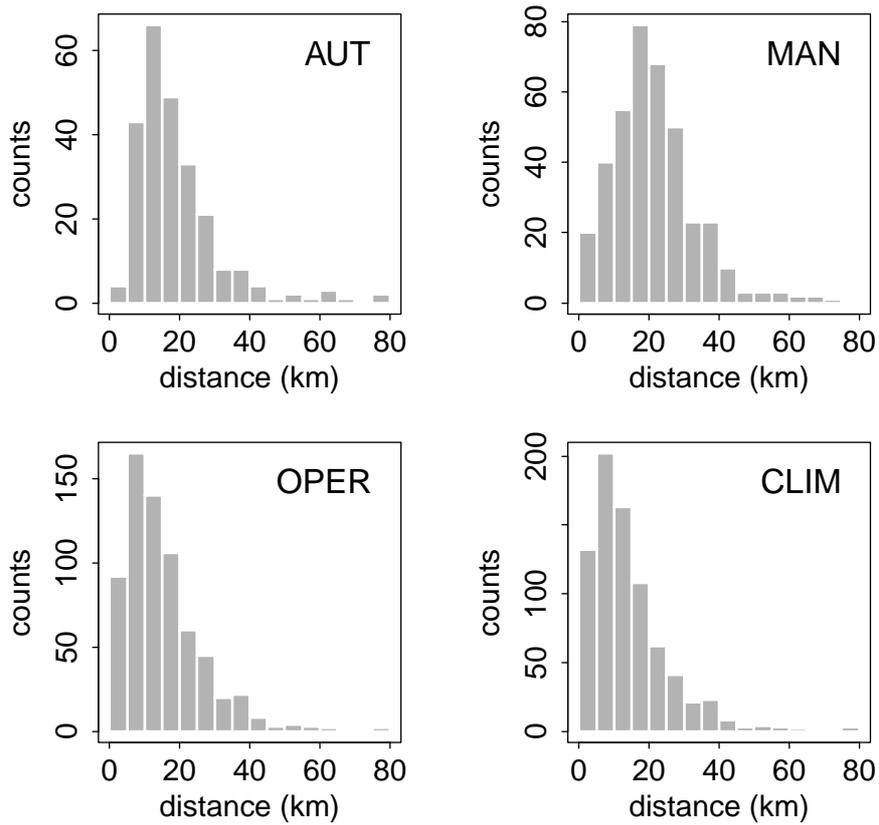


Figure 3.14: Histogram of triangular inter-station distances (Delauney triangulation) for four network combinations (coding see text). Only distances < 80 km are shown; the resolution is 5 km.

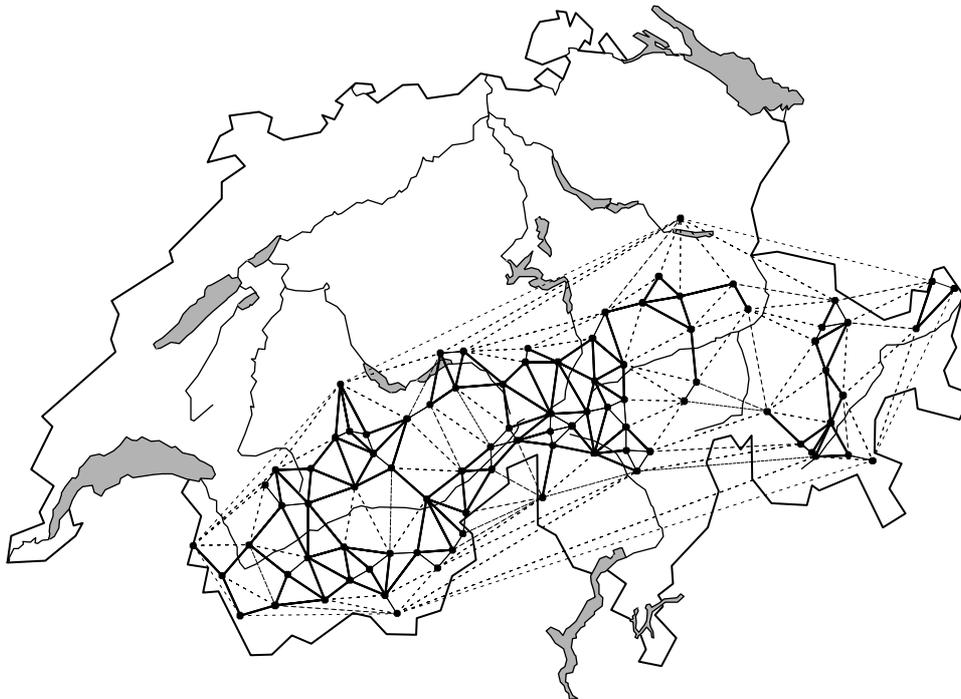


Figure 3.15: Delauney triangulation of the automatic stations network (AUT). Inter-station distances of 10 – 20 km (ideal) are thick solid, < 10 km thin solid and > 20 km thin dotted.

### 3.4 Discussion

Statements concerning the optimum spacing of a (snow) station network always depend on the purpose for which snow or other meteorological data is used. First, we have to specify the level for the minimum capture probability to be achieved. For large-scale analyses and rough overviews some single station data may be enough, the close surroundings of the stations are of no interest and CPs between stations may well be zero. But whenever local phenomena with a resolution of a few kilometres are analysed, CPs between stations should have a reasonably high value. An area-wide coverage with CPs of 100% or near 100% is unrealistic. However, as the situation with existing networks shows, 80% is much more realistic and provides still an acceptable probability level. For local avalanche warning purposes an 80% probability to make out heavy snowfall peaks is still higher than the overall prediction accuracy of about 65% (Brabec and Stucki, 1998; Föhn and Schweizer, 1995) and thus is acceptable. With CPs of 50% or lower, we must be aware that we miss at least half of all small snowfall events (slightly) exceeding our pre-set snowfall limit and thus avalanche forecasts will locally underestimate the situation in at least half of all cases.

This leads up to the second decision of general principle to be made in advance: Which snowfall limit is appropriate for our purposes? Snowfalls of 20 or 30 cm are hardly relevant for large spontaneous avalanches, but may significantly affect the hazard situation for self-triggered skier's avalanches and thus are relevant for the two most frequently issued avalanche hazard levels "moderate" and "considerable" (level 2 and 3 after the European avalanche hazard scale.<sup>5</sup> Figure 3.11 demonstrates that we are likely to capture nearly all (> 90%) HN20-events throughout most of the high mountain region, whereas HN30-events "only" yield a 80 – 90% catch rate. Local peaks of truly heavy snowfalls (HN50- or HN3/75-events), becoming relevant for disastrous avalanche situations (hazard levels 4 "large" and 5 "very large"), are even more difficult to be seen and yield capture probabilities in the range of only 60 – 80%. In principal the probability model can be based on any further snowfall limits. However, because very large snowfall events (e.g., HN100 or HN3/150) are increasingly rare the statistical data basis will become increasingly meagre.

An other point to remember using the model for real network evaluations are the initial assumptions we have made, mainly the isotropic, purely distance-dependent probability distribution. In reality many other circumstances such as topography and local climate

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<sup>5</sup> [http://www.sais.gov.uk/about\\_forecasts/hazard](http://www.sais.gov.uk/about_forecasts/hazard)

peculiarities disturb the ideal picture. Snowfall areas are always influenced by orographical divides. Two stations 30 km apart and separated by major topographic features have a different impact on the capture probability distribution between them, compared to two stations at the same distance but within the same valley. Also regional differences were not considered, since the model was constructed based on data from the entire Swiss Alps.

### 3.5 Conclusions

We have developed a tool to evaluate the effectiveness of the station density of snow station networks. Of course we could see before which areas were sparsely covered and which had rather many stations, but we had no quantitative arguments to determine the optimal spacing of a snow station network used for operational and climatological purposes. Although it does not hurt if a network is very dense, it may be far exaggerated, too costly and possibly senseless; depending on the purpose we may not gain much more valuable information out from this. For local applications needing a resolution of a few kilometres it is most ideal to have stations arranged as equilateral triangles with about 15 km side length and preferably at various altitudes to gain altitudinal diversity. Up to this distance we are able to capture at least 80% of all heavy snowfall events exceeding 30 cm. Beyond this optimum distance (high performance at low costs) we will miss more and more local events due to small-scale snowfall variability. A spacing of 20 km guarantees to catch only about 50% of all heavy snowfall events, which is already unacceptably low for many purposes.

The results in Figure 3.8 and 3.11 show unmistakably that the capture probability all along the national border is insufficient. Since it is likely that the surrounding countries have similar problems near their borders, the situation could be much improved by data exchange. Within Switzerland we must find ways to fill existing major gaps in our operational network. Thereby we should consider scenarios for the case some (or parts of) networks fail and data transmission between the two station managing institutions (SMA and SLF) is temporarily cut. Particularly serious is the situation on the southern slope of the Alps, not only in Ticino, but also in the southern valleys of the Grisons.

By all means of having found a quantitative way to measure the effectiveness of the snow station network, this is only one part of the entire snow station evaluation process. Before removing stations or designating places for new ones, other important factors have to be considered: 1) high-quality long-term stations must be preserved at all costs

in order to guarantee the continuation of valuable long-term climate series, 2) the practicability of existing observation and reporting methods must be checked (e.g., the conversion of monthly reporting into daily reporting stations), 3) the readiness of observers doing the job must be guaranteed, 4) the network reorganisation must be coordinated between SMA and SLF and 5) the finances for the whole concept must be available.

In future, additional studies comparing precipitation radar measurements (e.g., Li et al., 1995) with manual and automatic snow observations from terrestrial networks seem particularly fruitful. This may result in a better understanding of orographic precipitation effects and improve regional precipitation forecasts. However, for such studies data from the entire European Alps should be integrated.

### **Acknowledgements**

We would like to thank the Swiss Meteorological Institute for providing access to their climate database.

## Chapter 4

# Spatial Grouping of Snow Stations

*Manuscript:*

*Laternser, M. and Schneebeli, M.: Spatial grouping of Swiss snow stations by clustering. Submitted to Journal of Climate.*

### **Abstract**

Spatial grouping of snow stations is relevant for optimal interpolation and data aggregation. The traditional snow-climatological regions of the Swiss Alps are defined by major hydrological divides or district boundaries and are only partially comprehensible from the climatological point of view. Cluster analysis, based on 26-year long series of daily new snow (HN) and snow depth (HS) data, suggests a revision of the traditional division.

Depending on whether HN- or HS-data are taken as input for clustering, the outcome is different. Because the average snow depth is mainly a function of altitude, the resulting HS-clusters are strongly altitude dependent, widely overlapping and typically long-shaped parallel to the Alpine ridge, and thus not ideal for spatial grouping. On the other hand, HN-clusters, based on less altitude dependent single snowfall events, are more compact and form clearly defined areas spatially well separated from another. Therefore we promote the introduction of 10 – 14 new snow divisions primarily based on HN-data.

Optimal-sized HN-clusters are about 50 – 100 km long and 20 – 50 km wide covering areas of 1000 – 5000 km<sup>2</sup> of similar snow characteristics. Thus, about a dozen high-quality stations are needed to adequately monitor the general snow climate of the Swiss Alps. Differences between HN-clusters and the traditional snow regions are most obvious in the interior areas, where the main snow-climate divide cuts right across some traditional regions. The new grouping also provides quantitative information about the hierarchical relationship between neighbouring regions, offering new insight into the snow climatology of Switzerland.

## 4.1 Introduction

Knowledge of the spatial extent of homogeneous snow regions is relevant for data aggregation and optimal interpolation purposes: snow-climatological mapping, trend analyses, ski resort planning and operation, hydro-power management and snow hazard evaluation. Avalanche warning can benefit from statistically-derived boundaries between areas of similar snow conditions, indicating areas of a similar hazard estimation, whereas transient zones may direct the attention onto particularly critical areas. Extreme value analysis determining maximum possible snow increments on a certain location (e.g., for the design of avalanche defence structures) can be performed by including data from a wide range of similar stations. Particularly large homogeneous areas increase the data sample improving statistical estimates of rare events.

The Swiss Alps are traditionally divided into seven snow-climatological regions (Figure 4.1). The division was made decades ago based on the climatological experience at that time and goes back to the early years of the Swiss Army Avalanche Service during World War II and the foundation of the Swiss Federal Institute for Snow and Avalanche Research (SLF) in 1942. However, for a long time it has become evident that the original division is not optimal and early maps already show to some extent different dividing lines (SLF, 1952, p. 48). Although the traditional division is still commonly used for climatological purposes (e.g., Witmer et al., 1986), the Swiss avalanche warning service has used up to 121 variably aggregated small sub-divisions since 1996 (Brabec et al., 2000). However, this approach does not consider similarities between the individual units leading to a loss of the hierarchical relationship between neighbouring regions. Due to economical constraints the actual network of manually observing snow stations in Switzerland is presently evaluated with the aim of retaining only necessary stations. Thus, we applied cluster analysis to define groups of similar snow stations. The statistically derived groups are then compared to the traditional snow-climatological regions and revised snow-climate divisions for the Swiss Alps are proposed.

We could not detect much literature about previous work done on the regionalization of Alpine snow stations. However, a similar study was recently performed by Mock and Birkeland (2000), providing a new snow avalanche climate classification of the western United States mountain ranges. Sturm et al. (1995) proposed a new classification system for seasonal snow covers based on climate variables applicable for local to global scales and DeGaetano (2001) presented a method to group temperature and precipitation data of the United States.

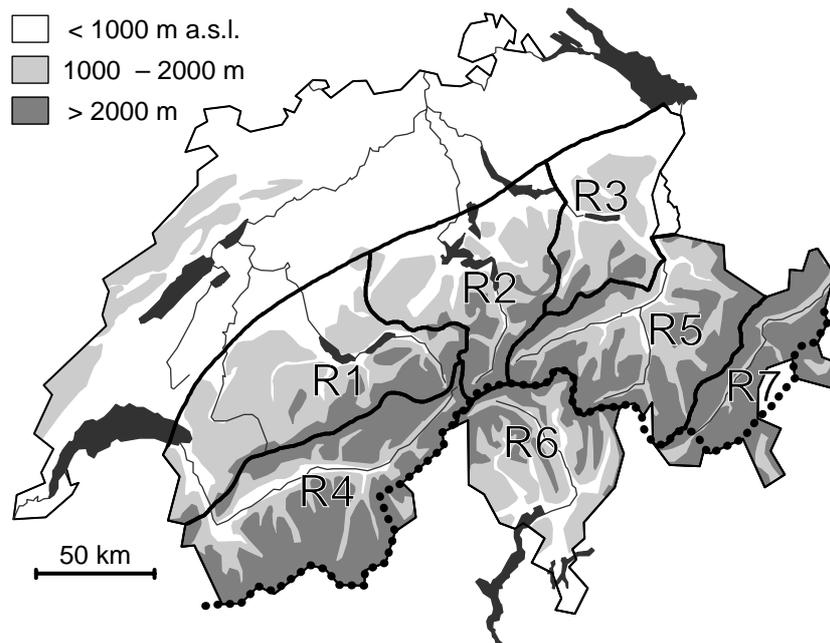


Figure 4.1: The seven traditional snow-climatological regions of Switzerland (R1 – R7), topography (grey scales) and Alpine main divide (dotted line).

## 4.2 Data

The analyses are based on daily snow depth (HS) and new snow (HN) data from the observational networks of the Swiss Meteorological Institute (SMA) and the Swiss Federal Institute for Snow and Avalanche Research (SLF). For the canton of Grisons (South-east Switzerland) additional data from the Rhaetian Railway (RhB) were used (HS only). We considered only quality-checked data covering the six-month winter season (Nov – Apr) from all available long-term stations at elevations of 1000 – 2500 m a.s.l. (see Chapter 2). The analysed period of time covers 26 years from 1970 – 1995 containing the highest station density; since 1995 the station numbers are shrinking again. This resulted in 133 applicable HS- and 100 HN-data series.

## 4.3 Method

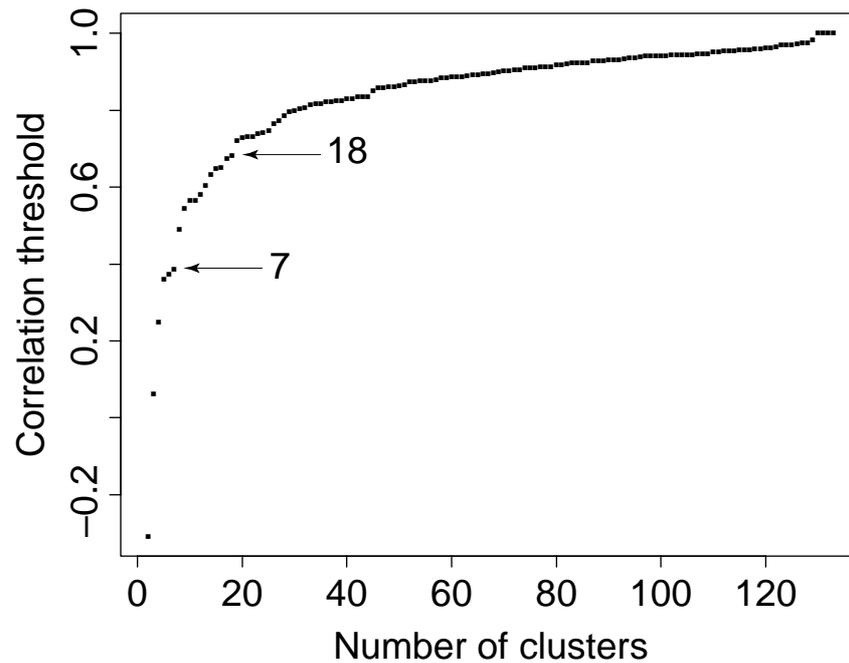
Station grouping was performed by hierarchical cluster analysis, a classical explorative tool in multivariate statistics for data grouping (e.g., Everitt, 1980). Whereas often distance measures are used to separate groups, we determined the correlation matrix between the different station time series in order to define groups of maximum similarity. All calculations were performed in S-Plus using the functions *cor*, *hclust*, *plclust* and *cutree* (StatSci, 1993).

In a first step the correlation between all stations was calculated. Not all stations have exactly the same period of observation and data gaps occur. Thus, it is impossible to correlate for all stations always the same winters with each other; the number of stations with unbroken snow series within the same period of time would be very small. Therefore each station is correlated with every other station during their maximum available common years, which means a different sample size for different station pairs. However, if more than five years in a common data period were missing, one or both stations (depending on the contribution to gaps with other stations) were omitted from further analysis.

The hierarchical cluster dendrogram reveals all grouping levels from one big cluster down to individual single-station clusters. Now we have to decide at which level we want to split the clusters, which is somewhat subjective. Either we prespecify an application driven correlation threshold above which clusters are separated or we decide in advance for an approximate number of clusters and make the cut before a major step of correlation increase. A more objective approach is suggested by DeGaetano (2001). He recommends to break at the point of maximum curvature of the relation between correlation threshold and number of clusters (Figure 4.2). In this analysis we chose two approaches: for a first coarse grouping we wanted to obtain about seven clusters (comparable to the seven traditional snow regions) actually cutting the cluster tree before a major step of correlation increase, and for the optimal fine grouping we applied DeGaetano's threshold selection rule.

## Results

First, clustering based on the correlation of daily HS-data was performed. The first few clusters split on a very low correlation level, but after every split the correlation markedly increases until five clusters are obtained (cf. Figure 4.2). Cluster 6 and 7 split at almost the same correlation level before a further marked increase occurs. This makes seven clusters a reasonable number for a first coarse division. Although this is the same number as the seven traditional regions, the spatial grouping obtained by clustering is very different: The clusters are extremely long-shaped parallel to the Alpine ridge and show a strong altitudinal dependence (Figure 4.3). Whereas traditional regions divide the northern slope of the Swiss Alps into three independent areas, the cluster analysis makes no division up to this correlation level in east – west direction. In reality, Clusters 1 – 4 are likely to cover the entire North Slope and the drawn boundaries depend solely on the availability of stations at certain altitudes. Thus, the entire North Slope is spatially one single HS-region, only vertically separated into sub-regions.



*Figure 4.2:* Number of clusters versus correlation threshold based on daily HS-data. A first coarse division is obtained after seven clusters and the point of maximum curvature followed by a jump of correlation increase after 18 clusters indicates the optimal correlation threshold for fine grouping suggested by DeGaetano (2001).

Also the traditional interior areas (Regions 4, 5 and 7) are not clearly separated from the remaining northern slope. By means of HS the western and northern Valais (R4) belongs clearly to the North Slope as well as the northern and eastern parts of the Grisons (R5 and R7). In the Upper Engadine (R7) the situation is even more complicated, since the high altitudes (mountain stations around 2000 m a.s.l.) show North Slope influence (right wing of Cluster 4), whereas lower altitudes (valley stations around 1700 m a.s.l.) are South Slope influenced (right wing of Cluster 6). Apart from that the conditions along the Alpine main crest are governed by southern influences and also on the actual South Slope a strong altitudinal dependence is visible.

Applying the correlation threshold selection rule after DeGaetano (2001) an optimal grouping of 18 clusters on a correlation level of 0.68 is attained (cf. Figure 4.2). The resulting clusters still depend on altitude and run long-shaped parallel to the Alpine ridge (Figure 4.4). Particularly on the northern slope of the Alps surprisingly large and overlapping clusters remain; Cluster 8 still ranges across the entire country from Lake Geneva to the Lower Engadine. However, the cluster size has shrunk considerably and east – west separations are more frequent. This is particularly well visible in the

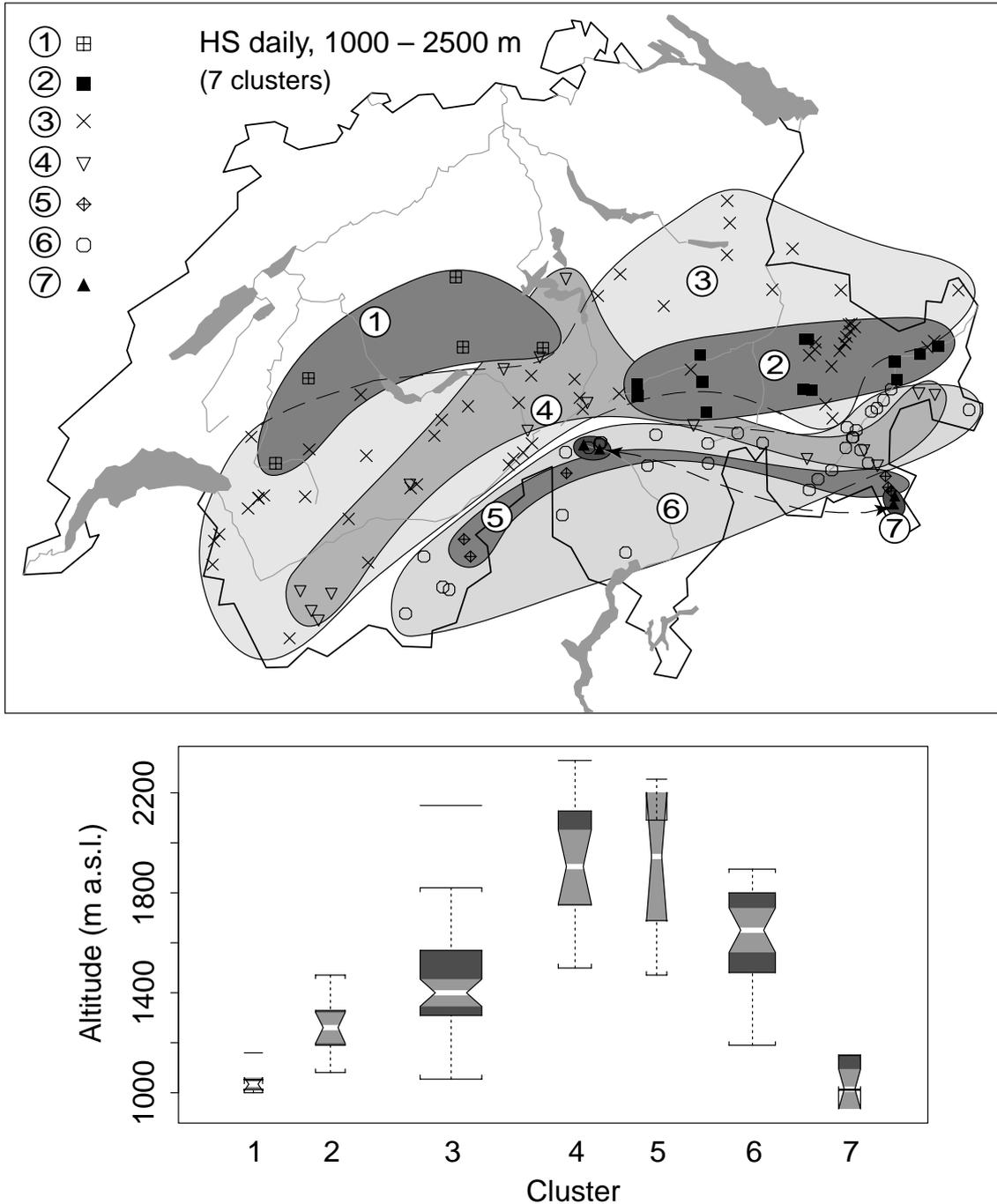


Figure 4.3: Seven main clusters based on daily HS-data from stations at elevations of 1000 – 2500 m a.s.l. (top) and corresponding altitude structure (bottom).

southerly influenced areas (southern Valais, Ticino, southern Grisons), where reasonably compact clusters formed. Figure 4.5 demonstrates the decreasing ratio between the mean long axis and the mean short axis for various numbers of clusters, proving that an increasing splitting of clusters generates more and more rounded cluster shapes, which are not necessarily in line with the Alpine crest anymore.

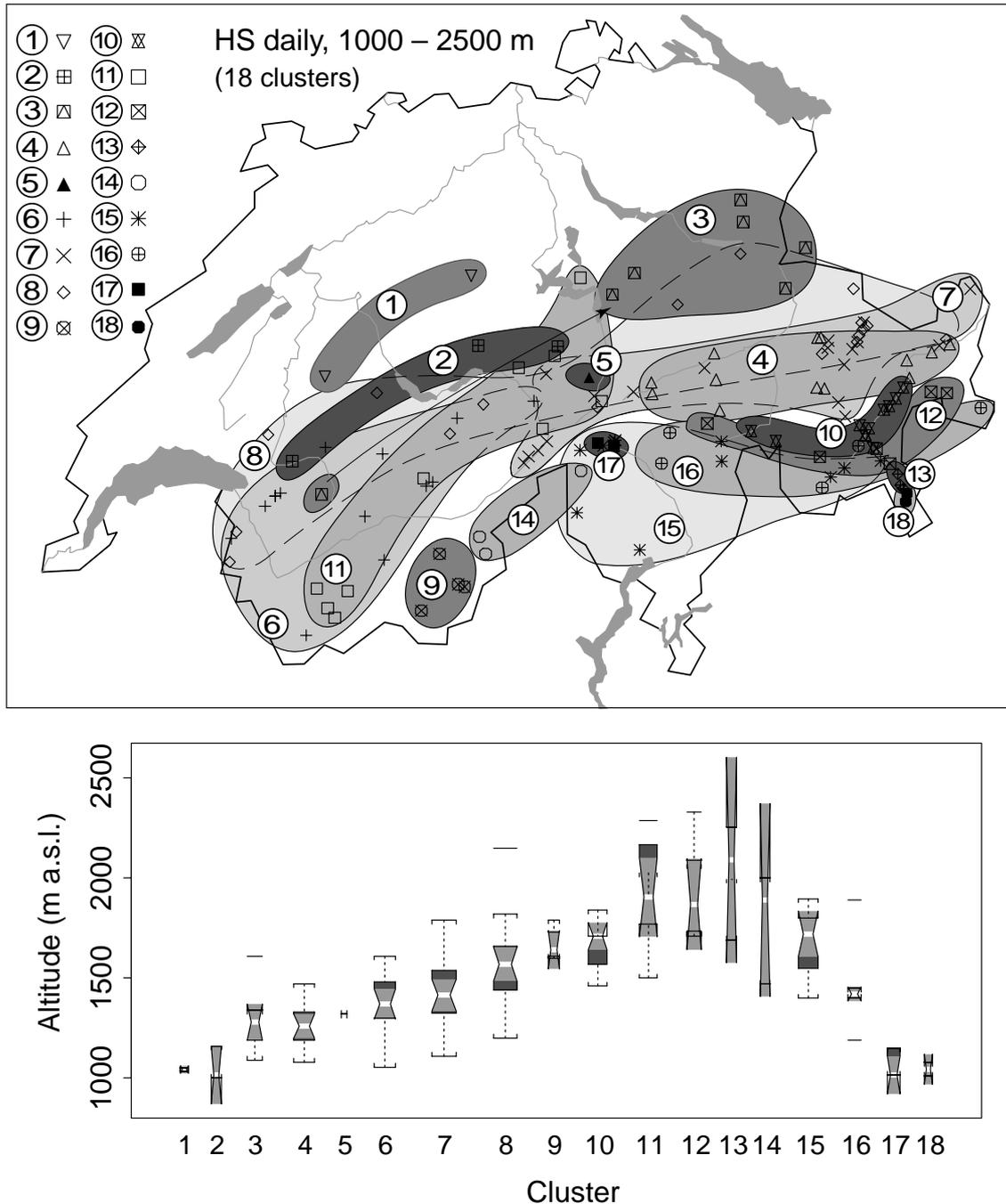


Figure 4.4: Eighteen optimal clusters based on daily HS-data from stations at elevations of 1000 – 2500 m a.s.l. (top) and corresponding altitude structure (bottom).

Clustering was also performed considering all elevations including stations below 1000 and above 2500 m a.s.l. However, the results were not very different except that the picture was even more cluttered up with overlapping clusters from very low and very high stations. On the other hand, restricting the elevation range of the input data even more to 1300 – 1800 m a.s.l. did obviously reduce the altitudinal dependence, but particularly on the northern slope long-shaped, overlapping clusters remained.

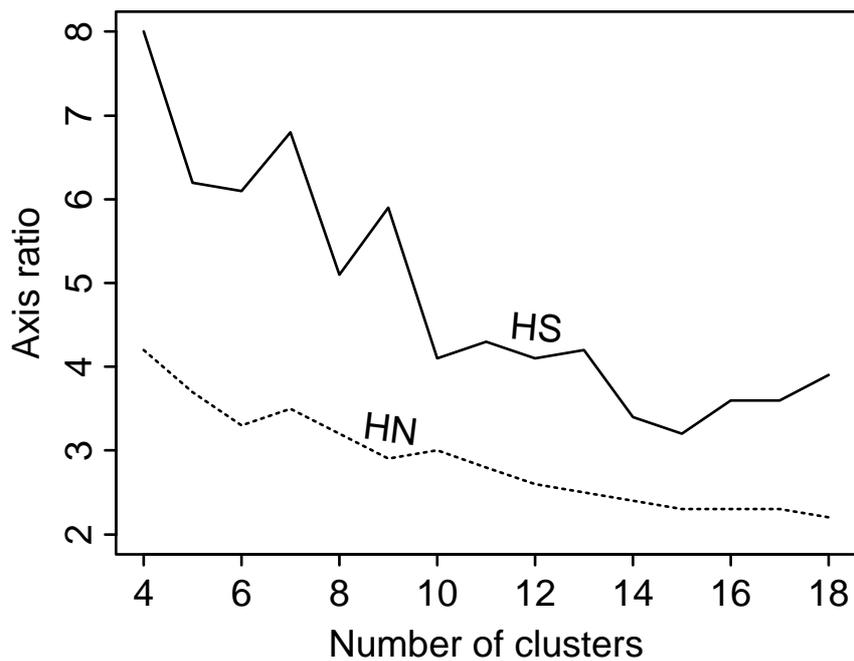


Figure 4.5: Ratio between the mean long axis and the mean short axis versus numbers of clusters based on HS-data (solid line) and HN-data (dotted line, see later in the text).

Additionally, the more we restrict the elevation range the less stations we get resulting in increasingly large areas lacking information. Using relative HS-data instead of absolute values (relative deviation of the mean annual winter snow depth from the long-term mean) did not much improve the picture, which was always governed by a strong altitudinal dependence and overlapping clusters.

In a second step daily new snow (HN) was analysed. HN directly reflects the precipitation pattern, has a very limited memory of the past weather conditions and is independent from the previous snow depth. Thus, HN is much less sensitive to altitude. This clearly revealed a case study for the Davos region (eastern Switzerland), where nine stations within 20 km radius of Davos at altitudes from 810 – 2540 m a.s.l. were analysed for HN – altitude gradients. For the 30-year period of 1970 – 1999 every snowfall day (November – April) with at least one station reporting  $\text{HN} \geq 1$  cm was selected. For each of the 2388 snowfall days the HN – altitude gradient was calculated by linear regression, resulting in a mean gradient of 0.34 cm HN increase per 100 m altitude gain (mean R-squared = 0.34). The median is only 0.22 cm/100 m and the histogram shows that a gradient of 0.0 – 0.1 cm/100 m is the most frequent case (Figure 4.6). Most often no or hardly any HN – altitude gradient exists when it snows, but the spatial snowfall variability is considerable (see Chapter 3). This doesn't make it

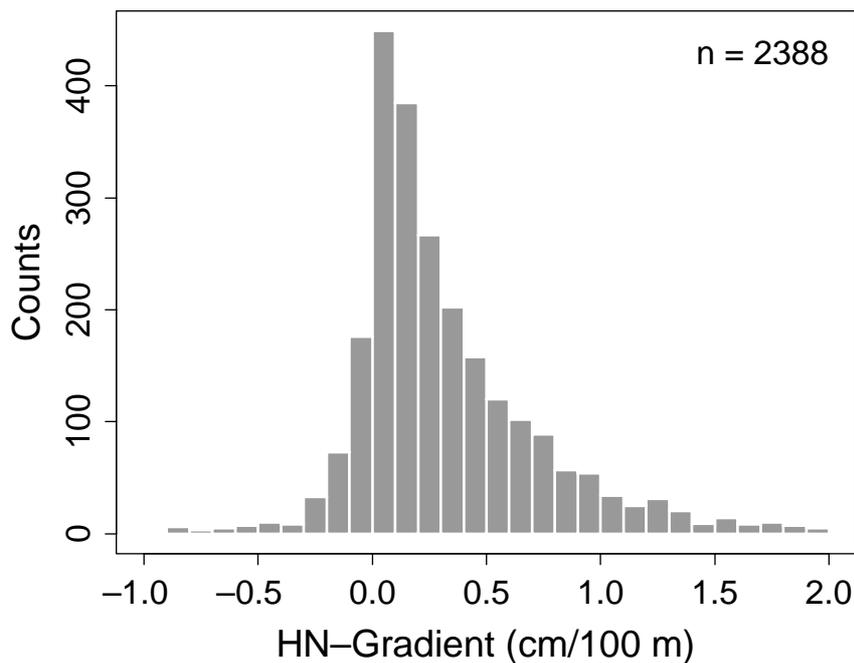


Figure 4.6: Histogram of HN – altitude gradients based on nine stations around Davos. No gradient is the most frequent case.

appropriate to calculate HN – altitude gradients across large areas, such as the entire Swiss Alps, because then the HN – altitude relation is essentially uncorrelated. 15 station pairs (short distance, large altitude difference) throughout Switzerland were also analysed for HN – altitude gradients and the findings were similar: mean gradient 0.76 cm/100 m, median gradient 0.48 cm/100 cm and most frequent gradient 0.1 cm/100 m.

As expected, clusters based on HN-data have no dominant altitudinal dependence. Although elongated shapes parallel to the Alpine crest remain, HN-clusters do not overlap anymore. Instead, they form clearly defined areas spatially well separated from another (Figure 4.7). The long-/short-axis ratio is clearly decreasing with a growing number of clusters and already starts on a much lower level as for HS, verifying the increasingly compact, roundish shape of HN-clusters (cf. Figure 4.5). According to the cluster tree after 5, 10 and 14 clusters major correlation steps suggest possible levels to split (Figure 4.8). The first split separates areas of greatest dissimilarity (correlation level 0.02) and divides the northern from the southern areas (thick line, Figure 4.7). However, this major snow-climatological dividing line does not follow along the topographical main divide, but generally lies north of it adding some of the interior areas to the south. Interestingly, this major divide cuts right across the traditional Regions 4 and 7 and even some southern parts of R5 (Hinterrhein) have southern

influence. The next split separates south-eastern Valais (C10 and C11) from the remaining southern areas (C12 – C14) and on the northern sector the North Slope (C1 – C3) is separated from the interior areas (C4 – C9) at virtually the same correlation level (thick dashed lines). Afterwards the interior areas split themselves into a western (C4 – C6) and eastern sector (C7 – C9, thick dotted line). So far we divided five major clusters, visualized by different grey scales in Figure 4.7 and of comparable size to the seven traditional snow regions. During the following five splits (medium solid lines) each major cluster splits again, resulting in 10 clusters visualized by different hatchings. Finally, four more splits (thin dashed lines) are necessary to reach the optimal number of 14 clusters on a correlation level of 0.61.

In order to minimize situations with rain at lower levels and snowfall higher up, what occurs primarily at the beginning and towards the end of the winter season up to about 2000 m a.s.l., clustering was performed also using the mid winter months January and February only. However, the results were very similar to the grouping based on the entire winter (November – April), confirming that rain at lower altitudes does not generally distort the grouping procedure.

#### 4.5 Discussion and conclusions

Depending on whether HN- or HS-data are taken as input for clustering, the outcome is quite different. Whereas HS-clusters are strongly altitude dependent, widely overlapping and typically long-shaped parallel to the Alpine ridge, HN-clusters are more compact and form clearly defined areas spatially well separated from another. This means dividing the comparatively small area of the Swiss Alps into numerous HS-regions makes hardly sense, because there are only two major regions: north and south. Obviously the long-term memory of HS, building up and degrading a snow cover in the course of an entire winter season, smoothes the typical small-scale variations found for HN. The altitudinal effect by far outreaches other regional variations, confirming that the average snow depth is first of all a function of altitude. This is primarily true for horizontal areas, where reference snow stations are supposed to be. On slopes the aspect (sunny/shady, windward/leeward) may become more important than altitude. On the other hand, HN-clusters are based on widely altitude *independent* single snowfall events revealing a large small-scale variability, and thus resulting in much clearer regional differences. Therefore we promote the introduction of new revised snow divisions primarily based on HN-data. Depending on the desired resolution, 10 – 14 new divisions are suggested (cf. Figure 4.7).

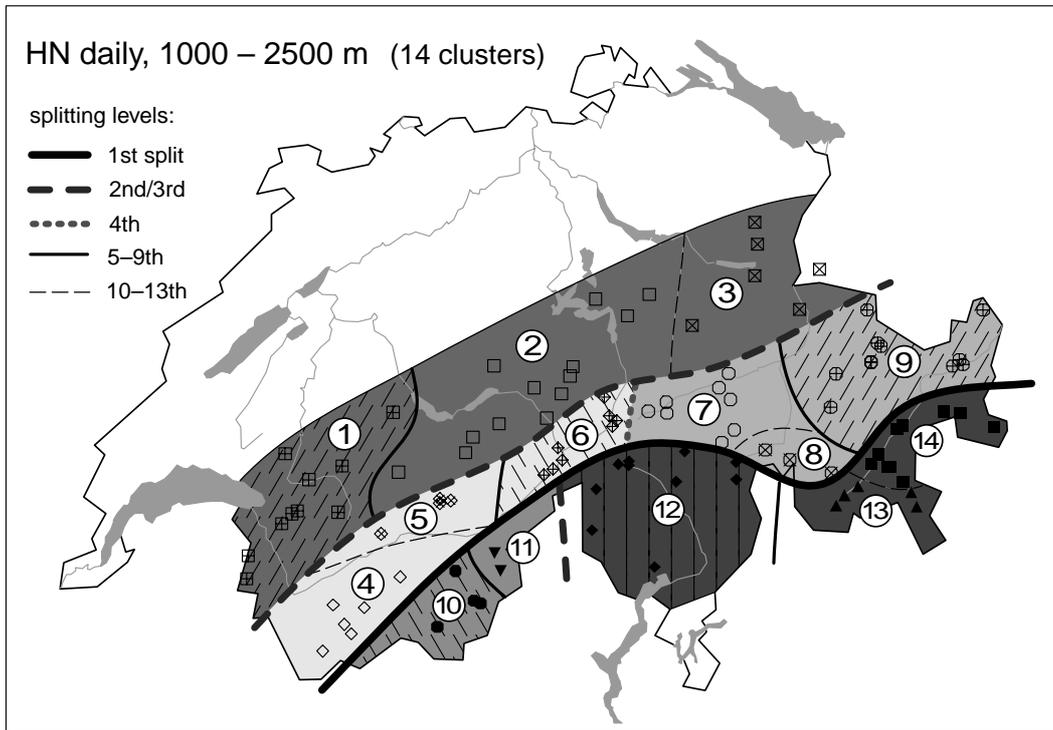


Figure 4.7: Fourteen clusters based on daily HN-data from stations at elevations of 1000 – 2500 m a.s.l. The line shape between the clusters visualizes the different splitting levels. The five major clusters are marked by different grey scales; the following five splits are emphasised by different hatching.

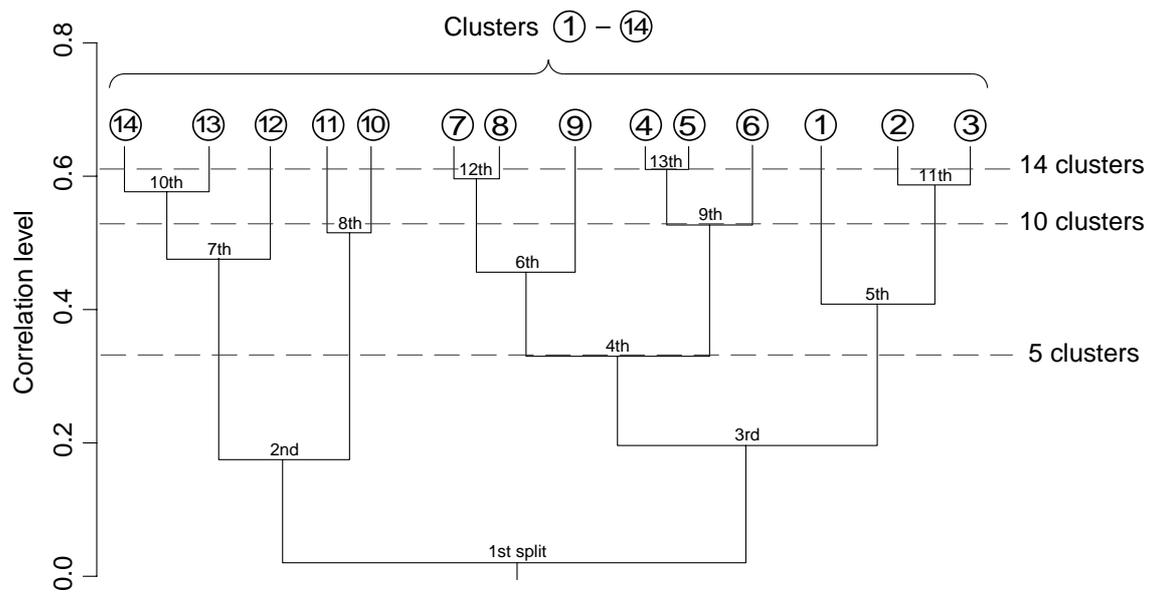


Figure 4.8: Cluster tree for the first fourteen clusters based on HN-data.

Optimal-sized HN-clusters are about 50 – 100 km long and 20 – 50 km wide, resulting in areas of 1000 – 5000 km<sup>2</sup> of similar snowfall characteristics. Assuming that one station per cluster is sufficient to represent the general snow climate, we would need about a dozen high-quality stations to adequately monitor the snow climate of the Swiss Alps. However, this is far too less for small-scale applications such as local avalanche warning (see Chapter 3). With the new snow divisions we would cover at least a medium elevation range of about 1000 – 2500 m a.s.l., which is most important for an accurate allocation of snow resources (winter tourism, avalanche warning, hydro-power management). Areas below 1000 m do not well fit into the proposed regionalization scheme, because low levels normally do not feature a regular snow cover and thus are also less important to be incorporated into snow divisions. On the other hand, high-altitude areas above 2500 m seem to be governed again by a different regime. However, because data hardly exists from reliable long-term high-altitude stations, the spatial snow variability in the high mountain zone is not well known, despite the significance for hydro-power management and avalanche warning is indisputable. Since medium hazard levels (“moderate” and “considerable”) prevail during most of the winter season and touristic activities under these conditions are widespread throughout the (high) mountains, it is most desirable to accurately assess the largely variable snow and avalanche situation also at high altitudes in order to prevent touristic avalanche accidents. In this sense, a great potential starts to open up by the widespread and increasing installation of automatically recording high-altitude snow stations since the 1990s.

Whereas the traditional snow-climatological regions of the Swiss Alps are defined by major hydrological divides or district boundaries, the new revised divisions are climatologically more comprehensible. Differences between HN-clusters (Figure 4.7) and the traditional snow regions (Figure 4.1) are most obvious in the interior areas, where the main snow-climate divide cuts right across the traditional Regions 4 and 7. R4 (Valais) consists of five new clusters, demonstrating the great heterogeneity of this region. That the Simplon area (a South Slope valley, C11) belongs to the southern part is obvious. But apparently also the entire Visp valleys (interior, C10) are strongly influenced by the south. Further to the east the entire Upper Engadin as far as Pass dal Fuorn has southern influence (together with the southern valleys of Müstair, Poschiavo and Bregaglia; C13 and C14), but the Lower Engadine and Samnaun split away from the traditional Region 7 joining the interior Cluster 9. In the eastern part Cluster 12 (former R6, Ticino) even reaches slightly across the Alpine main divide incorporating Hinterrhein (former R5). Obviously the southern-most areas of the interior valleys are well sheltered from precipitation from the north and receive most of their snow across the main divide from the south.

North of the main snow-climate divide the interior areas are well separated from the North Slope, as it used to be in the traditional division. However, striking are the weak differences along most of the North Slope. Three quarters of the area (C2 and C3) separate only at the 11th splitting level, showing clearly the very strong similarities within this area. Only the western-most part (C1) soon splits away from the remaining North Slope, but the boundary between C1 and C2 is much further west than the traditional boundary between R1 and R2. Noteworthy constellations within the interior areas are Cluster 6, joining the Upper Valais (Goms) together with southern Uri, and Cluster 8, dividing southern Mittelbünden from the remaining traditional R5. In an experimental clustering run based on HN-data from 1300 – 1800 m a.s.l. only, C8 and the southern-most station of C7 (Zervreila) even joined together with C14 (Upper Engadin), thus proving the strong connections of southern Mittelbünden to the South Slope.

The occurrence of obviously ridge-parallel clusters makes clear that an analysis including snow data from the neighbouring countries (France, Italy, Austria, Germany) would be very useful to create Alpine-wide continuous snow regions. It is presumed that all South Slope clusters (C10 – C14) do not stop at the border, but would continue into neighbouring Italy. Clusters 1 and 4 are likely to spread west into France (Chablais, Région du Mont Blanc) and Clusters 3 and 9 probably continue east into Austria (Vorarlberg and Tyrol). However, confined to Switzerland the snow climate variability is obviously stronger in the interior and southern areas than in the north, what implies that the station density should be higher in the interior and south in order to representatively monitor the snow climate; but exactly the opposite is true (see Chapter 3). The reason for the larger North Slope clusters compared to the interior areas is that the North Slope is most often influenced by air flows from the same main direction (N – W) causing a more homogeneous snow distribution. On the other hand, the interior regions receive snow from several directions resulting in more heterogeneous snow characteristics.

The fact that snow-climatological variations are much more pronounced in north – south direction compared to east – west has consequences for various applications based on snow data: 1) Spatial interpolation (e.g., kriging) with an isotropic approach is unsatisfactory. 2) The probabilistic model determining the capture probability of heavy snowfall events (see Chapter 3) could be based on an elliptic probability distribution rather than on circles. 3) Regional and local avalanche warning will be facing steeper gradients of changing snow conditions in north – south direction compared to east – west, making it easier to accurately predict the avalanche hazard along the northern

slope than in the interior areas. Especially this last point is of great importance and proves that snow conditions can change drastically within a few kilometres of distance while we may not be able to monitor this due to lacking observation stations. In order to fully comprehend the strong north – south gradient, the station density should be higher along transects across the Alps than in ridge parallel direction. Additionally, to obtain an optimal station grouping for operational purposes (avalanche warning, touristic snow reports, etc.), clustering could be performed on a daily basis considering respective HN-series of the ongoing winter.

### **Acknowledgements**

We would like to thank the Swiss Meteorological Institute for providing access to their climate database and the Rhaetian Railway for regularly delivering their snow depth data to our institute.

## Chapter 5

# Temporal Trend and Spatial Distribution of Avalanche Activity

*Accepted paper:*

*Latarnser, M. and Schneebeli, M., 2002: Temporal trend and spatial distribution of avalanche activity during the last 50 years in Switzerland. Natural Hazards (in press).*

### **Abstract**

Avalanche observations are an important factor for the 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.

## 5.1 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 Schneebeili (1995) contains numerous more sources describing early avalanche events prior to 1950 and Schneebeili 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, 2002). 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 informations 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., 2000).

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.

## 5.2 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 5.1, Table 5.1). 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. 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 5.2).

Table 5.1a: 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.

<i>Code</i>	<i>Station name</i>	<i>Altitude (m a.s.l.)</i>	<i>Observation period</i>	<i>Years with observations</i>	<i>L5-Quality (mean)</i>
1HB	Hasliberg	1830	1960 – 1999 *	37	0.2
1MR	Mürren	1660	1951 – 1999	49	1.2
1GB	Grindelwald Bort	1570	1951 – <b>1991</b>	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 – <b>1995</b>	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
3SW	Schwägälp	1290	1967 – 1999 *	36	1.1
3MG	St. Margrethenberg	1190	1954 – <b>1994</b> *	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 – <b>1998</b> *	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
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 5.1b: 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.

<i>Code</i>	<i>Station name</i>	<i>Altitude (m a.s.l.)</i>	<i>Observation period</i>	<i>Years with observations</i>	<i>L5-Quality (mean)</i>
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	Gurtellen	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	Innerglass	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

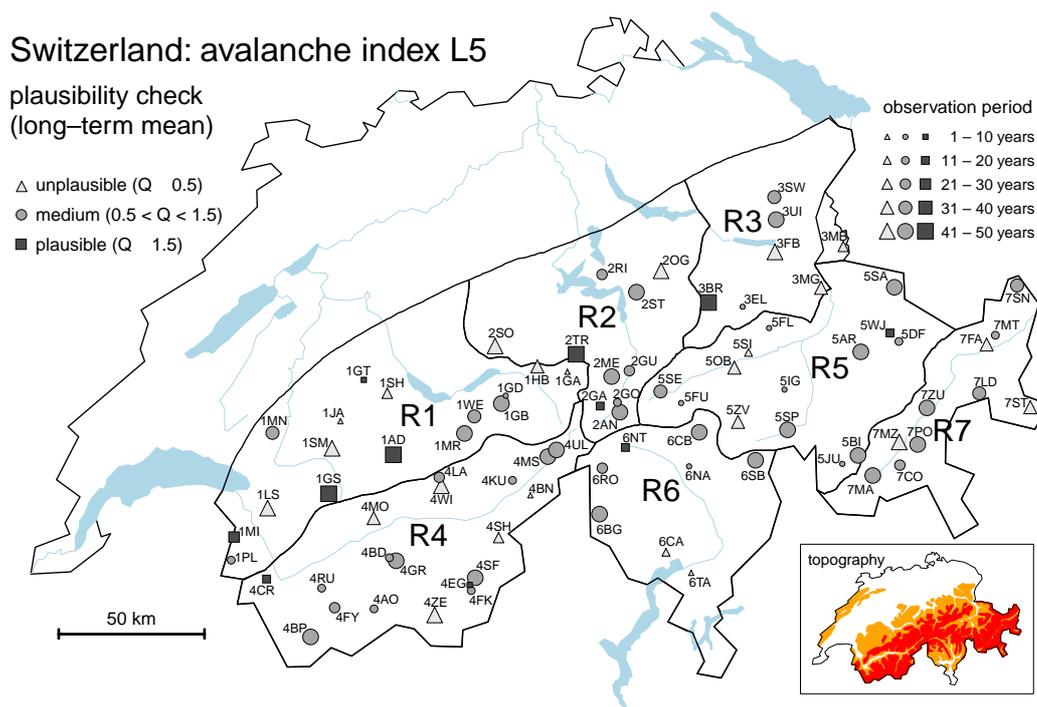


Figure 5.1: Map of Switzerland with the SLF avalanche observation station network (station labels in Table 5.1). The dot size indicates the length of the observation period. Also shown is the station rating according to the quality of the avalanche observations (mean of the annual classification; see 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.).

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 5.2, 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 5.3.2.

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 5.4.2 and 5.4.4.

Table 5.2: 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).

<i>L5</i>	<i>Number, size and impact of avalanches</i>
/	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

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, what shows the subjectivity of observations which can not be measured with a standard instrument. Thus, avalanche observation data need extensive preprocessing to become statistically treatable as a whole (Section 5.3.1). This is somewhat different as for 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, 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 5.1). 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 5.2): 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. The situation has only improved in the course of the last three years.

**Ulrichen** (Figure 5.3): 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 somewhat 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 the 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.

## 5.3 Methodology

### 5.3.1 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

## Avalanche Observations Münster

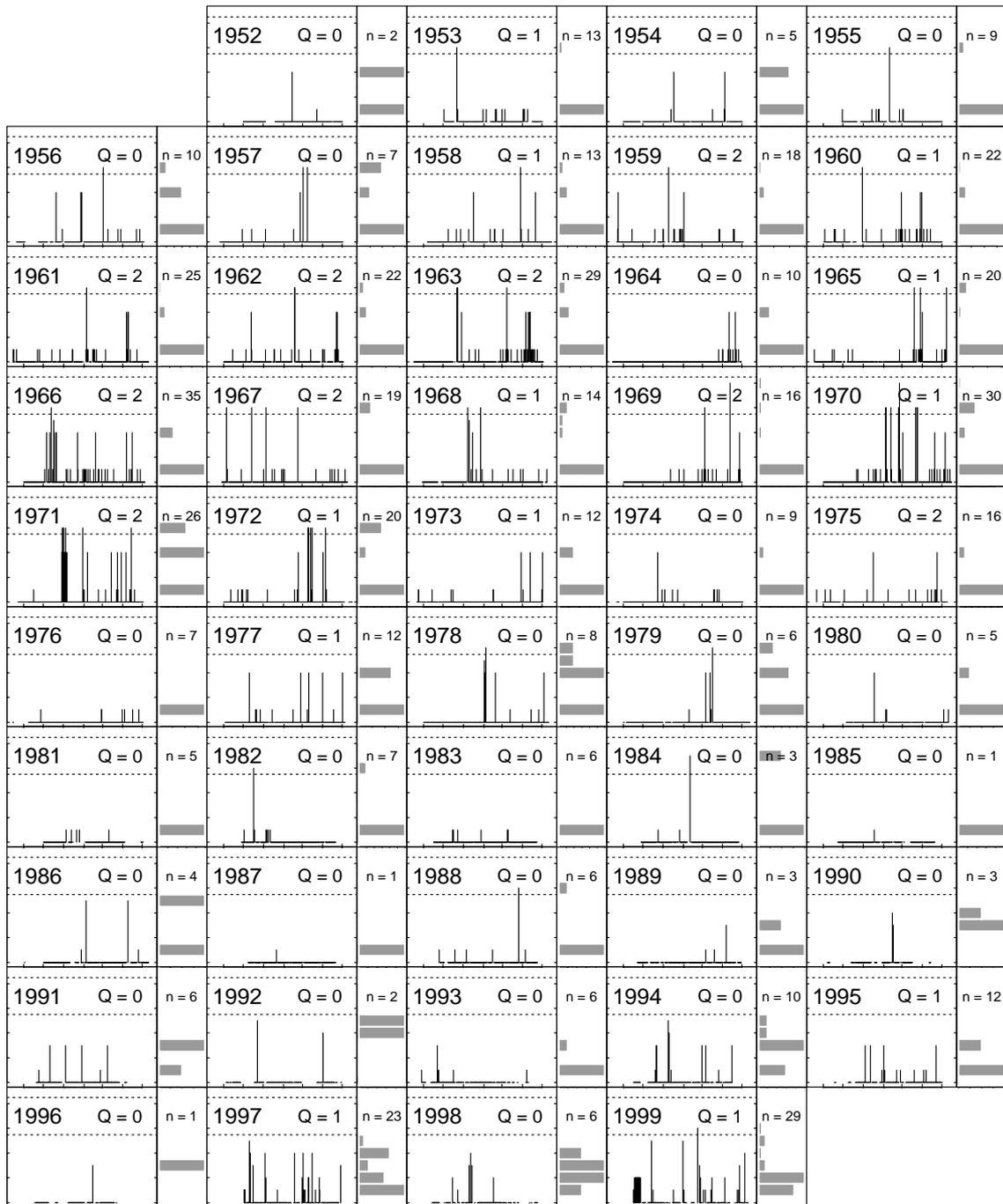


Figure 5.2: Avalanche Index  $L_5$  (impact, number and size) of Münster for the winters 1951/52 – 1998/99.  $Q$  is the automatically classified data quality (0 = implausible, 1 = medium, 2 = plausible).  $n$  is the total number of days with observed avalanches ( $L_5 > 0$ ). For further details see Figure 5.4.

## Avalanche Observations Ulrichen

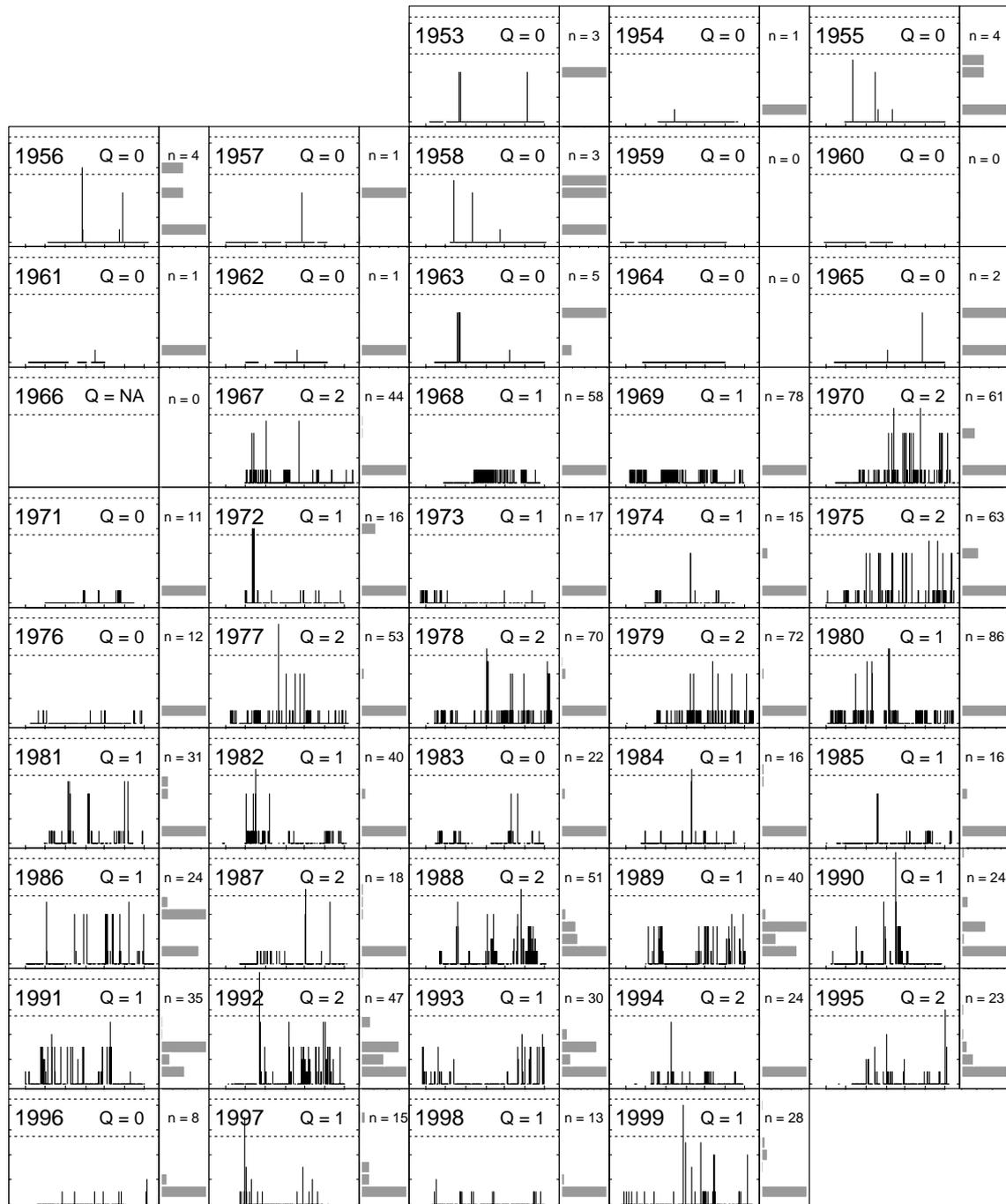
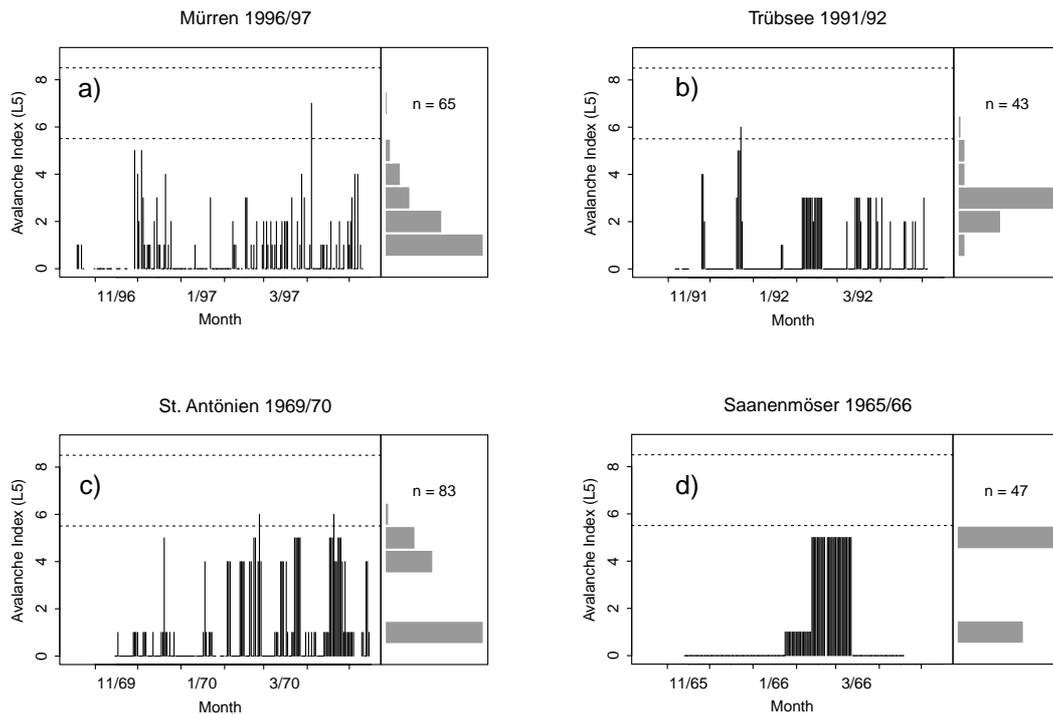


Figure 5.3: Avalanche Index  $L_5$  (impact, number and size) of Ulrichen for the winters 1952/53 – 1998/99.  $Q$  is the automatically classified data quality (0 = implausible, 1 = medium, 2 = plausible).  $n$  is the total number of days with observed avalanches ( $L_5 > 0$ ). For further details see Figure 5.4.

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 5.4). NA stands for missing values. Expressed as a pseudo code the criterions look as follows (for criterions labeled with \* see additional details further below):

- 0) if(all(AO) = NA) → Q = NA [no observations → no classification!]
- 1) if( $S \leq 10$ ) → Q = 0
- 2)\* if( $S < q_{10}$ ) → Q = 0  
 but if histogram has
  - at least two levels
  - and higher level is at most +1 of next lower level → Q = 1
- 3)\* if( $q_{10} \leq S < q_{25}$ ) → Q = 1  
 but if only one level → 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 → Q = 2
- 4) if( $q_{25} \leq S < q_{50}$ ) → Q = 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 → Q = 2
- 5) if( $S \geq q_{50}$ ) → 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 → Q = 2
- 6)\* if more than 7 successive missing values → Q ≤ 1  
 if more than 20 successive missing values → Q = 0



*Figure 5.4:* 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 5.2; 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) Müren, 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.

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 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.

### 5.3.2 Transformation from categoric to ordered data

The Avalanche Index L5 has a mixed ordered-categoric scale (Table 5.2). 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 5.1) 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  $\leq 5$ , and

then to replace codes  $> 5$  by two substitute classes depending on this average. The quality-weighted mean (M1) is calculated using the formula

$$M1 = \sum(L5_{[0-5]} \cdot QW) / \sum QW \quad (5.1)$$

with  $L5_{[0-5]} = L5\text{-codes} \leq 5$  and  $QW = \text{quality weights}$ . 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  $M1 \leq 3$ , 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  $\leq 5$  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.

### 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 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 5.5). 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 (5.1), but this time all L5-codes are considered, including the transformed original codes  $> 5$ :

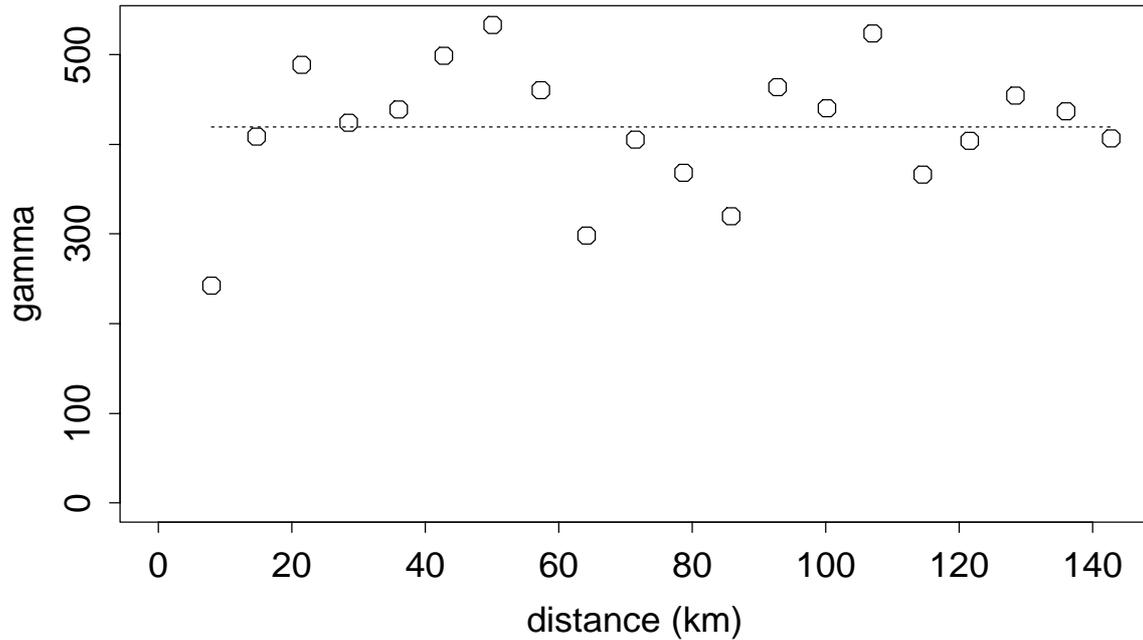


Figure 5.5: Empirical variogram of avalanche observation data (number of days with observed avalanches) from winter 1998/99. The semivariance (gamma) is rapidly increasing and after the first lag stations are spatially uncorrelated.

$$RAAI = \frac{\sum(L5_{all} \cdot QW)}{\sum QW} \quad (5.2)$$

with  $L5_{all}$  = L5-code of the original codes  $\leq 5$  and the transformed, original codes  $> 5$ . QW are the same quality weights as in Equation (5.1). 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.

## 5.4 Results

### 5.4.1 Quality control of avalanche observation stations

With the plausibility check the data quality of all stations can be classified for every winter. Figure 5.1 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 5.1.

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 5.2) or to compare the observations with other avalanche data archives, such as the DADB. This latter approach will be outlined in Section 5.4.3.

### 5.4.2 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 5.6 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 5.1) 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.

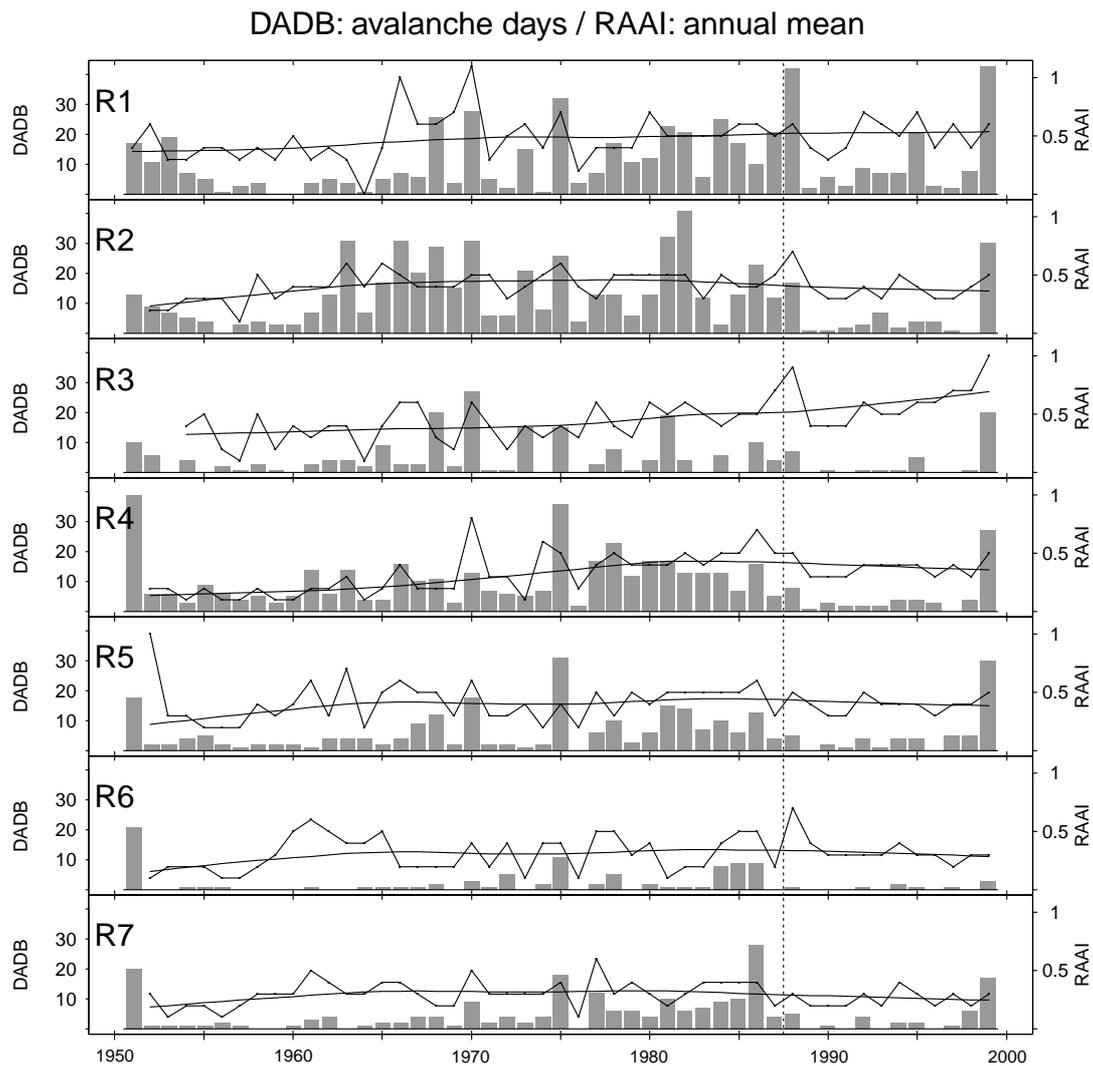


Figure 5.6: Annual number of avalanche days according to the DADB (bars) and annual RAAI-mean (jagged line) including a lowess-smoother (smooth line) for all seven regions during the period 1951 – 1999. The dashed line indicates the AO-code change in 1987/88. “Skier avalanches” are excluded from the DADB; only spontaneously released destructive avalanches are shown.

The annual RAAI-maximum shows a slightly more diverse picture (Figure 5.7). 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 5.8) 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.

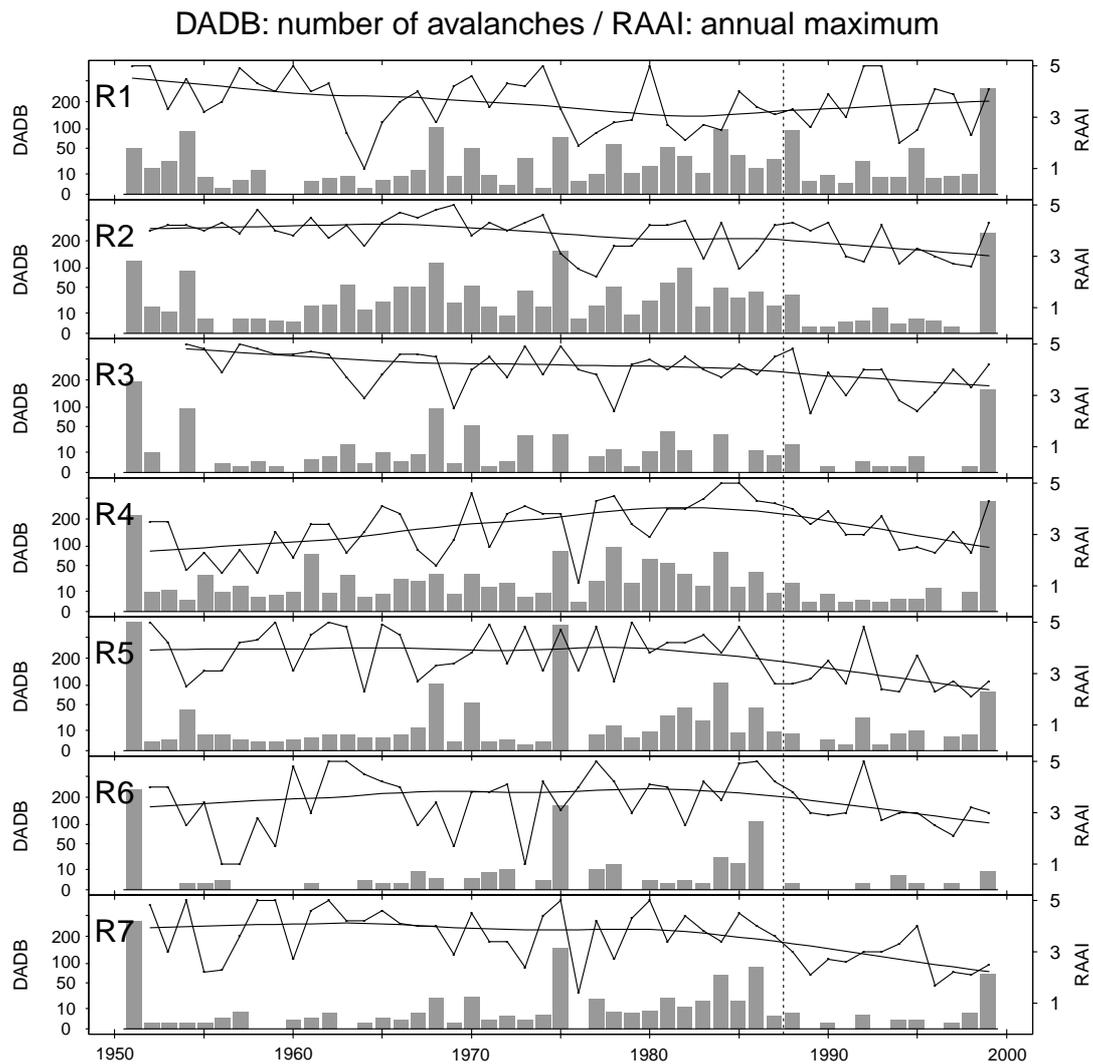
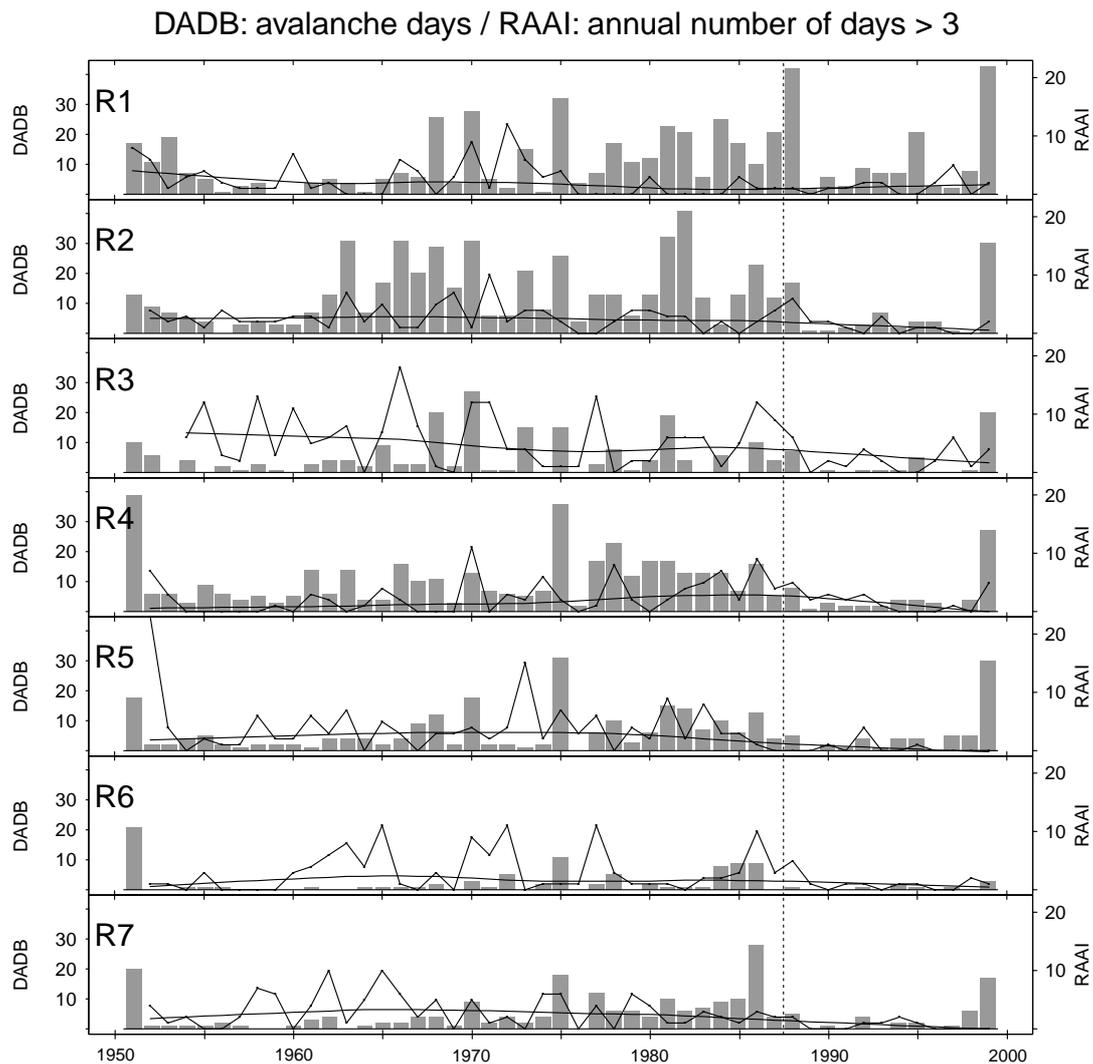


Figure 5.7: Annual number of avalanches according to the DADB (bars, square-root-transformed scale) and annual RAAI-maximum (jagged line) including a lowess-smoother (smooth line) for all seven regions during the period 1951 – 1999. The dashed line indicates the AO-code change in 1987/88. “Skier avalanches” are excluded from the DADB; only spontaneously released destructive avalanches are shown.

Additionally and for comparison, Figures 5.6 – 5.8 show the number of avalanche days (Figure 5.7 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.



*Figure 5.8:* 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.

### 5.4.3 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 avalanche 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 5.9). 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 5.9) 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 5.9c), 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)

## DADB vs. Avalanche Index L5 Andermatt

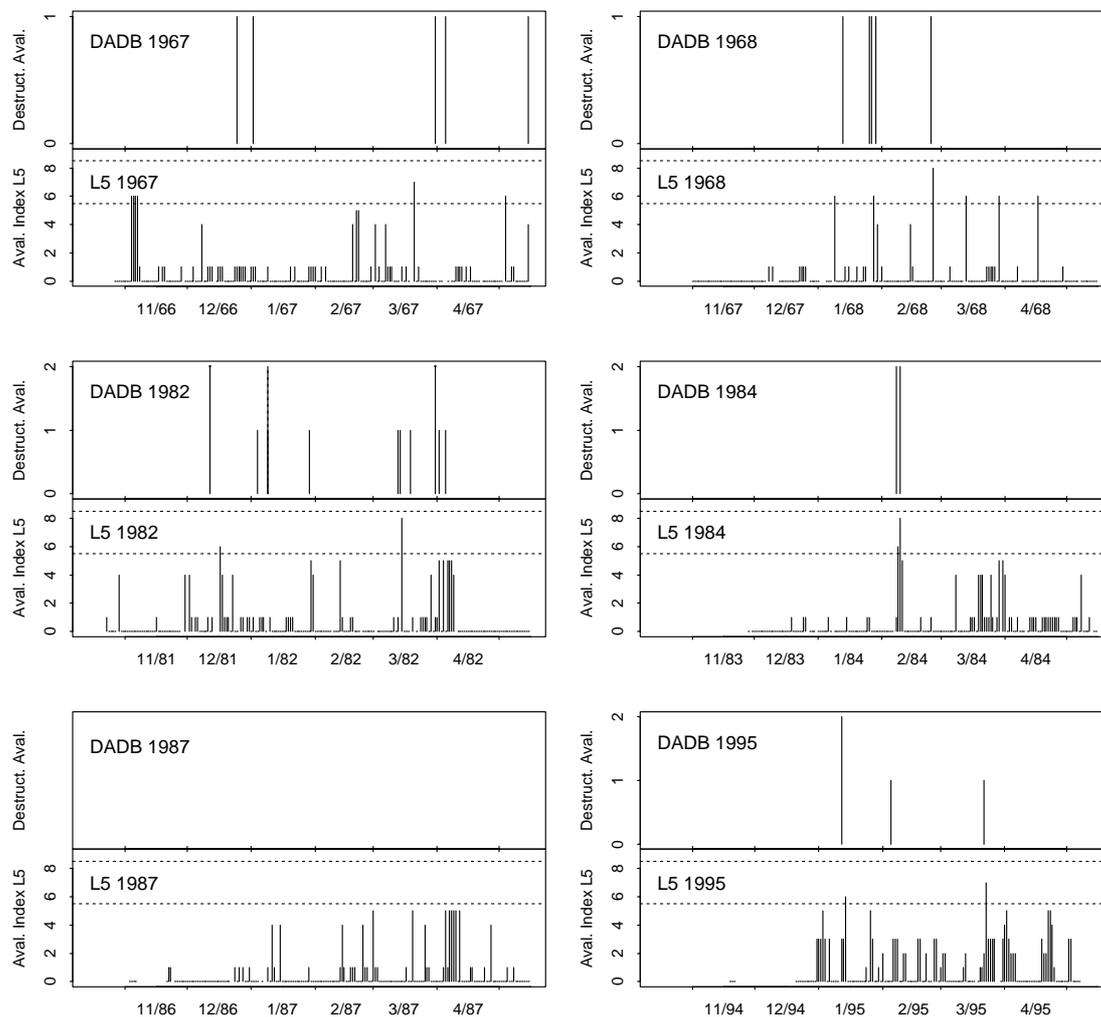


Figure 5.9: Six winters with daily comparison between the Destructive Avalanches Database (DADB) and Avalanche Index L5 for Andermatt. The upper part of each plot shows the number of destructive avalanches from the DADB (note the different scales!) and the lower part of each plot contains the Avalanche 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 another 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 DADB nor observations show 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.

## DADB vs. Avalanche Index L5 Hasliberg

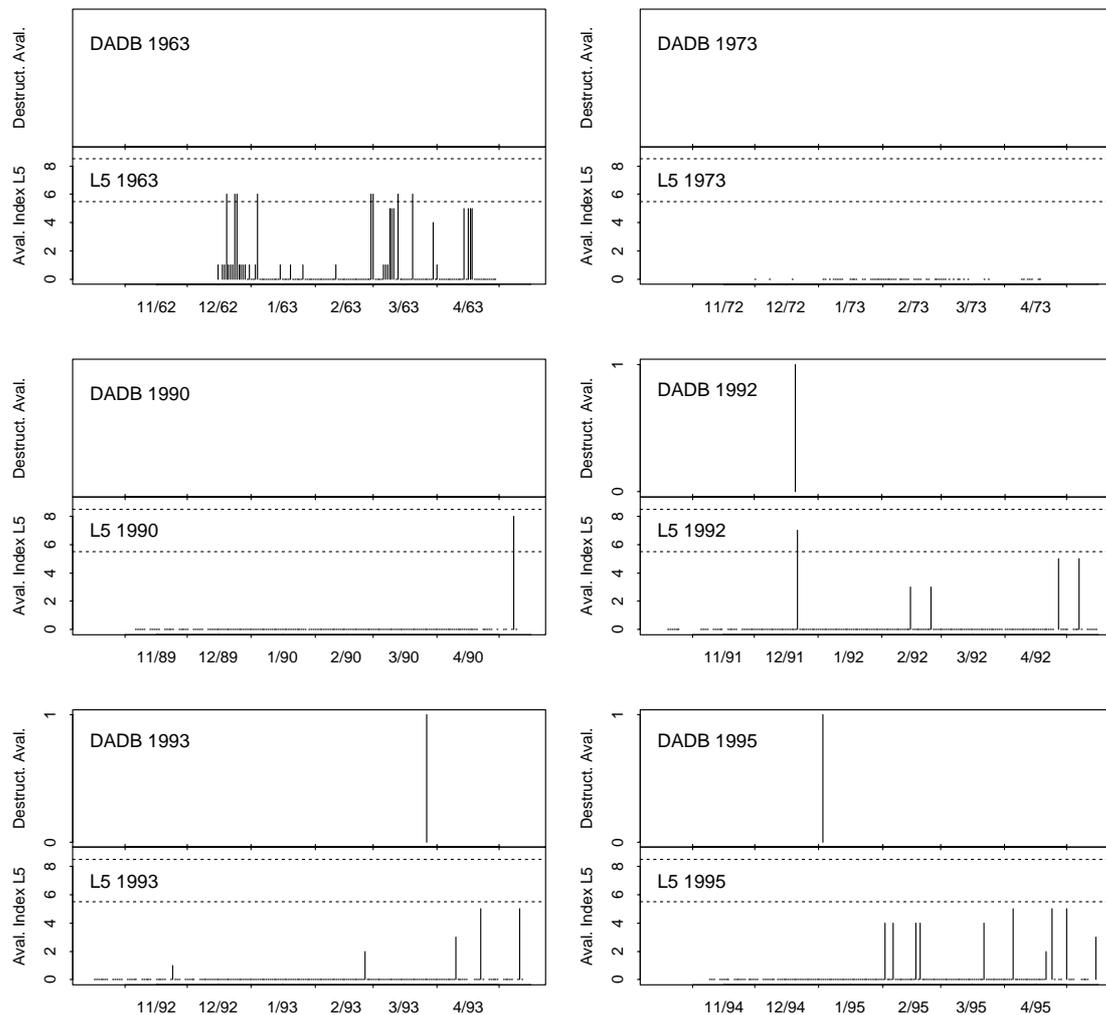


Figure 5.10: As Figure 5.9, but for Hasliberg.

- 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.

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 5.10e and 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 5.10c)!

#### 5.4.4 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 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 5.11 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 (“×” in Figure 5.11 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 5.12 shows all situations with more 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 did not attain more than  $RAAI = 3$ , 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).

## RAAI vs. DADB (1951 – 1999)

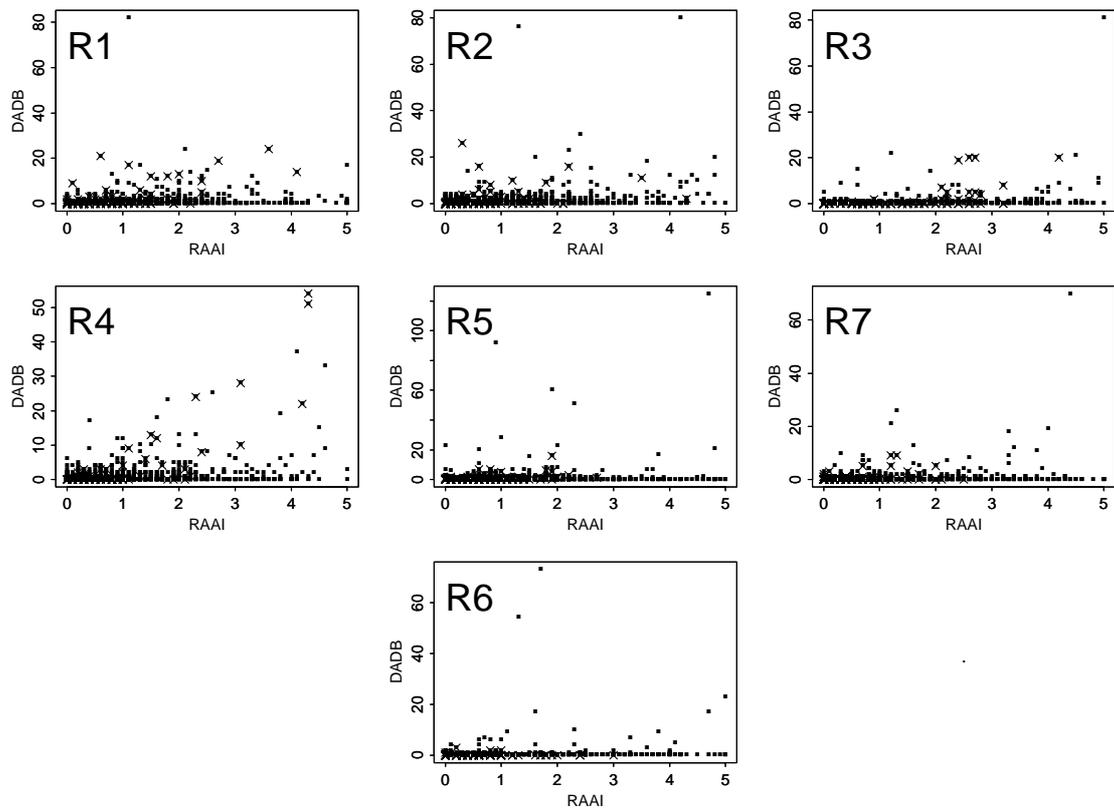


Figure 5.11: Regional Avalanche Activity Index (RAAI) versus total number of destructive avalanches from the DADB in daily resolution from 1951 – 1999 and for all seven regions R1 – R7. Strictly speaking a certain day of the RAAI was compared with the previous day from the DADB. Values of the most recent winter 1998/99 are plotted as “x”.

A slightly different approach is visualized in Figure 5.13, 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 by destructive avalanches in the DADB. For this situation, three explanations are possible: 1) by far not all situations with several big avalanches do actually cause destructions, what seems not very likely to us, 2) the DADB is incomplete, what is not believed to be the case to this extent, or 3) 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.

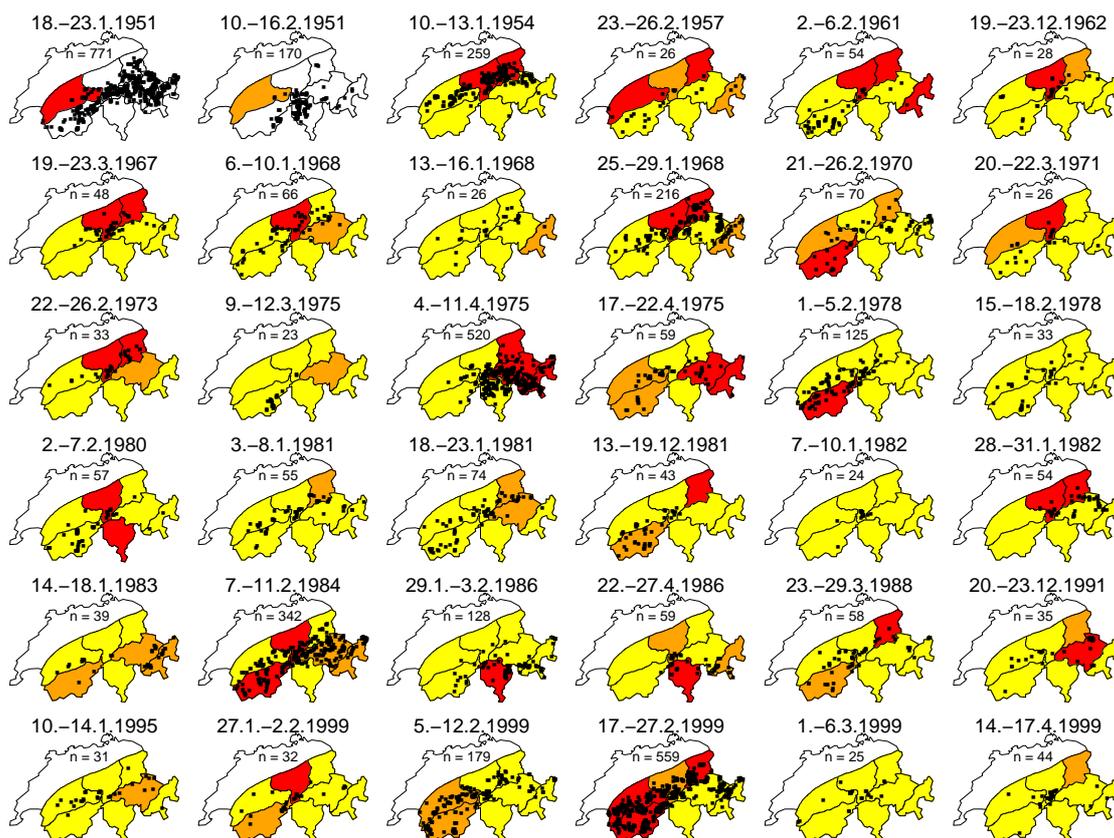


Figure 5.12: All situations with more than 20 destructive avalanches within two days (dots) from 1951 – 1999, overlaid by the highest RAAI during these periods for every region (grey areas). The three grey scales represent  $RAAI \leq 3$  (light grey),  $3 < RAAI \leq 4$  (medium grey),  $RAAI > 4$  (dark grey); white areas stand for “no observations”.  $n$  is the total number of destructive avalanches.

## 5.5 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 5.12 and 5.13, situations with high observed avalanche activity do not coincide well with

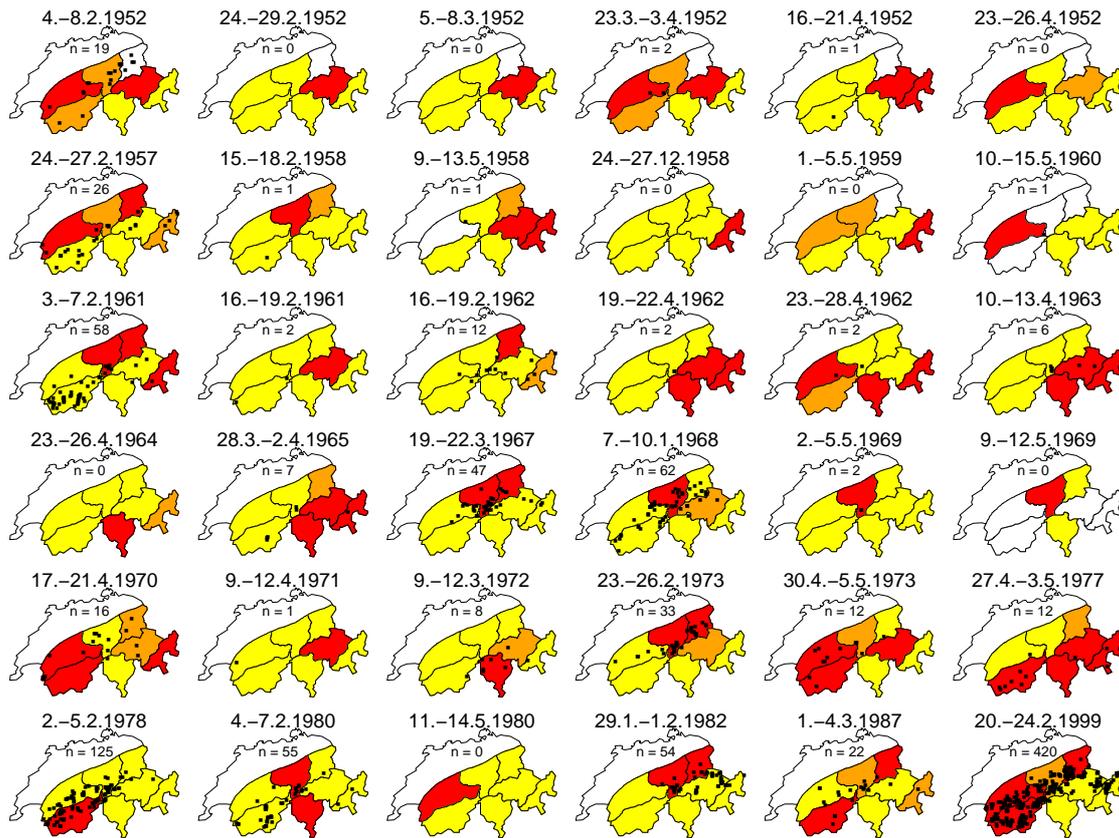


Figure 5.13: All situations with RAAI > 4 for at least two successive days and in at least one region (grey areas) from 1951 – 1999, overlaid by the destructive avalanches (dots) during these periods. The three grey scales represent RAAI  $\leq 3$  (light grey),  $3 < \text{RAAI} \leq 4$  (medium grey), RAAI > 4 (dark grey); white areas stand for “no observations”.  $n$  is the total number of destructive avalanches.

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 5.4.2, 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 Schär (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 5.14). However, consideration of only destructive avalanches can be problematic for various reasons: 1) Sometimes it is rather by chance that an avalanche causes damage or not; it can stop a few metres above a railway line and then will not be recorded. 2) 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 to be destroyed by the following avalanches a few years later. 3) Constructional protective measures change the probability of an avalanche release and the run-out distance of avalanches. 4) 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 observation 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.

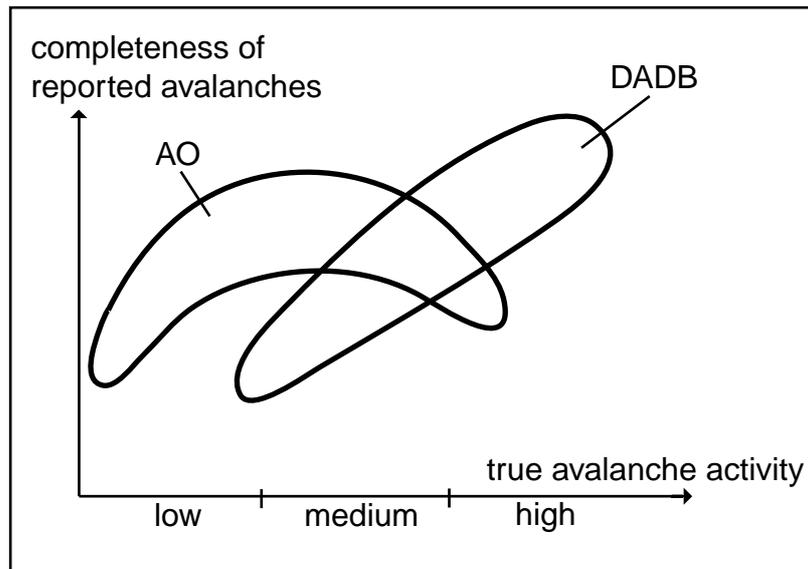


Figure 5.14: Completeness of avalanche observations (AO) and the destructive avalanches database (DADB) under various degrees of avalanche activity. The AO seem to reach a climax in medium avalanche activity, but then decrease again because of many missing values in situations of high avalanche activity. 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.

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., 2000) and seismic techniques (Ammann, 1998; Suriñach et al., 2000) 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.

## Chapter 6

# Conclusions and Outlook

This thesis contributes to a better understanding of the snow and avalanche climatology of Switzerland. For the first time nationwide long-term trend analyses of various snow parameters are presented. Trends from 1931 – 1999 are calculated for the mean seasonal snow depth, the duration, beginning and final dates of snow cover, the number of snowfall days and for heavy snowfall events. The results are of high relevance in the current climate change debate and well fit northern hemisphere snow trends found in the literature: a general increase — with interruptions — until the early 1980s followed by a statistically significant decrease towards the end of the century. Changes are amplified at low elevations. However, data processing clearly demonstrated that in order to monitor subtle climatic changes, superimposed by large regional, altitudinal and annual variations, a sufficiently dense network of continuous snow stations resulting in homogeneous long-term series is necessary.

This leads to the second main topic of this thesis, how to determine an optimal station density for various issues. Particularly for local avalanche warning it is crucial to know whether or not we will miss small-scaled heavy snowfall peaks in unmonitored country. The developed probabilistic model shows that ideal networks should have a triangular spacing of about 15 km in order to obtain a spatially continuous snowfall capture probability of at least 80%. Spacings of 20 km result in only 50% guaranteed capture probability, which means we will miss at least half of all local snowfall peaks in areas of maximum distance between stations and thus avalanche forecasts will locally underestimate the situation in at least half of all cases. Although the Swiss operational snow observation network widely reaches capture probabilities of 80% and more, serious deficiency areas exist all along the national border and in the south/south-east. Thus, future reorganization of snow station networks should be determined to close existing gaps. This can be achieved by first of all checking the availability of nearby foreign stations and initiating cross-border data exchange. However, in some cases we will not get away without setting up new stations, but as a countermove it should be affordable to close existing stations in unnecessarily densely covered areas.

The seven snow-climatological regions of the Swiss Alps have a long tradition, are deeply anchored in the minds of generations of scientists and serve for many applications. Nevertheless, it is urgently encouraged to adapt to a new, climatologically more comprehensive division as outlined in Chapter 4. Good reasons for a change are manifold. Most applications dealing with the spatial interpolation of snow data revert to snow regions, be it for the calculation of regional altitude gradients or for the estimation of snow conditions for avalanche warning. Using inaccurate divisions obviously affects the result in a bad way. However, snow regions are not firmly fixed, but change in time. For analyses based on average climate conditions the newly proposed divisions are fine. But looking at single years or even single days, the region boundaries can be quite different depending on recent snowfalls and weather conditions. For such studies, ideally, cluster analysis based on the correlation coefficient between the used time-series should be applied every time afresh. To obtain an optimal station grouping for operational purposes (avalanche warning, touristic snow information, etc.) it is even recommended to perform clustering on a daily basis considering the entire snow series of the ongoing winter. In this sense it would have been more appropriate to calculate the Regional Avalanche Activity Index (RAAI, Section 5.3.3) for the new snow climate divisions instead of using the traditional regions. However, the manuscript for Chapter 5 was processed well before the regionalisation was done, and it remains to be verified that the RAAI based on new divisions would perform much better than the RAAI applied to the old regions.

Concerning avalanche activity it became obvious how difficult it is to obtain reliable and consistent avalanche observations. As the word says, it is a subjective observation and not a reproducible measurement, bringing a natural heterogeneity into the data. Beside general quality concerns the most disturbing fact is that in adverse weather often no “observation” is possible and thus particularly avalanche-prone situations remain unmonitored. Since avalanche activity data are the only way to carry out an objective verification of the issued avalanche forecast, it is urgently recommended to intensify research developing man- and weather-independent systems recording avalanche activity. Any approaches based on acoustic (Adam et al., 1998; Duclos et al., 2000) and seismic techniques (Ammann, 1998; Suriñach et al., 2000) do not yield satisfying results yet. However, from the climatological point of view neither general avalanche activity nor disastrous avalanches show obvious trends during the last 50 years. Typical is a very large variability from year to year, which has been reconstructed for destructive avalanches back to the 15th century (Latenser and Pfister, 1997; Schneebeli et al., 1998).

As an outlook, several more issues can be addressed to for future work: Based on the newly aggregated dataset of homogeneous long-term snow series and the sound knowledge of climatologically comprehensive snow regions, the production of a new revised map showing seasonal and monthly snow depths of Switzerland could be tackled and published as a new HADES-sheet (cf. LHG, 1992). The last such snow climate map (SMA, 1987) dates back 20 years and is based on 20 years data from 1960/61 – 1979/80 (Witmer et al., 1986). Thus, the basic data period could be doubled or at least extended to the climatological standard period of 1960 – 1990, and in the meantime newly developed techniques could be applied. Schwarb et al. (2001) recently published similar maps featuring the mean annual and seasonal precipitation throughout the European Alps 1971 – 1990, based on PRISM, a statistical-topographic model for mapping precipitation over mountainous terrain (Daly et al., 1994; Schwarb, 2000). As for precipitation, a new snow climate map should integrate the entire Alpine region and not be confined to the Swiss Alps only.

Both for average climate mapping and for the operational production of daily new snow and snow depth maps<sup>6</sup> the problem arises using accurate HN- and HS-altitude gradients for spatial interpolation. Whereas PRISM applies weighted altitude regression of neighbouring stations under consideration of topography, traditional methods work with regionally defined altitude gradients. Based on the proposed new snow-climate divisions, the promising “optimal interpolation approach” developed by Durben (2001) should enable to produce much better results, particularly after the integration of snow data from automatic stations. At the moment, automatic stations are excluded in Durben’s model, because data series are still too short; but this will change after a few more years.

Also for extreme value analysis new possibilities open up. Whereas the classical Gumbel method (Gumbel, 1958) should definitely be replaced by more modern approaches (e.g., Chavez-Demoulin, 1999; Coles, 2001), data from several stations within homogeneous snow regions can be aggregated and analysed jointly in order to increase the data sample and thus improving statistical estimates of rare events. This seems particularly significant for applications based on maximum possible snow increments (determination of snow loads for engineering purposes, planning of avalanche defence structures, avalanche hazard mapping).

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<sup>6</sup> <http://www.slf.ch/avalanche/hsr-dec.html>

In Switzerland and throughout the European Alps snow is a resource of great commercial value (winter tourism, temporary reservoir for drinking water, irrigation and hydro-electricity). At the same time snow bears considerable hazards such as heavy loads on constructions, road closures and avalanches. Thus, adequate monitoring of snowfall and snow depth is an important social task. The two observational networks of the Swiss Meteorological Institute (SMA) and the Swiss Federal Institute for Snow and Avalanche Research (SLF) contribute since decades to an increasingly successful “snow management”. However, this thesis uncovers various weak points of today’s snow monitoring system and allows to draw conclusions to be considered for the evaluation and reorganization of the existing scheme.

The ultimate goal in order to attain a superior snow observation network should be 1) to preserve high-quality long-term stations for climate monitoring, 2) to maintain an evenly distributed number of stations divided into climatologically comprehensible regions and 3) to cooperate Alpine-wide allowing for cross-border data exchange. Within Switzerland the SMA- and SLF-snow stations should be jointly operated and snow data stored in a common database. A well-balanced mixture of rather low- to medium-elevated man-served observation stations and automatic high-altitude stations should be retained. Since all neighbouring countries will be facing similar problems in their border areas, an Alpine-wide snow data exchange will be beneficial for all parties. Particularly the avalanche warning services will get more reliable informations from the border areas, avoiding that these regions remain delicate zones. With the aim of achieving a highly resolved, area-wide aquisition of snowfall data in future, a strong input should be given to the development of improved precipitation radar techniques or other space- and airborne “snowfall detectors”.

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# *Curriculum Vitae*

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*Name*                 Martin Christian Laternser  
*Date of Birth*       19 July 1966  
*Citizen of*           Zurich/ZH  
*Nationality*         Swiss

## **Education and Professional Career**

*1973 – 1979*        Primary School in Hombrechtikon/ZH

*1979 – 1985*        High School in Wetzikon/ZH; Matura Typus C

*1986 – 1992*        Studies at the Swiss Federal Institute of Technology (ETH) in Zurich;  
Division of Earth Sciences, Dept. of Geography, specialising in glaciology

*Nov 88–Jan 89*     Full time English school, Milner International College, Perth, Australia

*Jul–Sep 1990*     Glacio-meteorological expedition to Greenland (Dept. of Geography, ETHZ)

*April 1992*         Graduation as “dipl. Natw. ETH”;  
Diploma thesis: *Firn temperature measurements in the Swiss Alps*

*May 1992*          Snow-hydrological field trip to Greenland (GGU Copenhagen)

*Jun–Aug 1992*     Glaciological traverse across the Greenland ice sheet (VAW/ETH Zurich,  
University of Heidelberg and TU Braunschweig) followed by data analyses at  
the Laboratory of Hydraulics, Hydrology and Glaciology (VAW/ETHZ)

*1994 – 2001*        Research assistant, later Ph.D. student at the Swiss Federal Institute for Snow  
and Avalanche Research (SLF) in Davos

Main research activities:

- NFP31-project *Interactions between climate, avalanches and technical measures* (as part of the Swiss National Science Foundation programme *Climate changes and natural disasters*)
- Set up of the SLF-Destructive Avalanches Database
- Project coordinator of the *Turkish – Swiss research and development project on avalanche warning and risk prevention*
- Consultant for research on *Climate change effects on mudflows and snow avalanches in Kazakstan* and for the *Reactivation of the avalanche warning service in Kazakstan*
- Major contributions to analyses about causes and effects of the disastrous avalanche winter 1999 in Switzerland
- Dissertation about *Snow and avalanche climatology of Switzerland*

*Sep 97–Mar 99*     Postgraduate course in applied statistics, Statistics Seminar of ETH Zurich