INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **33**: 3162–3173 (2013)

(wileyonlinelibrary.com) DOI: 10.1002/joc.3653

Snow variability in the Swiss Alps 1864–2009

Simon C. Scherrer,[a] Christian Wüthrich,[a,b] Mischa Croci-Maspoli,[a] Rolf Weingartner[c]
and Christof Appenzeller[a]

[a] *Climate Division, Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland*
[b] *Amt für Umweltschutz Kanton Uri, Altdorf, Switzerland*
[c] *Group for Hydrology, Institute of Geography, University of Berne, Switzerland*

ABSTRACT: We present a climate analysis of nine unique Swiss Alpine new snow series that have been newly digitized. The stations cover different altitudes (450–1860 m asl) and all time series cover more than 100 years (one from 1864 to 2009). In addition, data from 71 stations for the last 50–80 years for new snow and snow depth are analysed to get a more complete picture of the Swiss Alpine snow variability. Important snow climate indicators such as new snow sums (NSS), maximum new snow (MAXNS) and days with snowfall (DWSF) are calculated and variability and trends analysed. Series of days with snow pack (DWSP) $\geq$ 1 cm are reconstructed with useful quality for six stations using the daily new snow, local temperature and precipitation data. Our results reveal large decadal variability with phases of low and high values for NSS, DWSF and DWSP. For most stations NSS, DWSF and DWSP show the lowest values recorded and unprecedented negative trends in the late 1980s and 1990s. For MAXNS, however, no clear trends and smaller decadal variability are found but very large MAXNS values (>60 cm) are missing since the year 2000. The fraction of NSS and DWSP in different seasons (autumn, winter and spring) has changed only slightly over the ~150 year record. Some decreases most likely attributable to temperature changes in the last 50 years are found for spring, especially for NSS at low stations. Both the NSS and DWSP snow indicators show a trend reversal in most recent years (since 2000), especially at low and medium altitudes. This is consistent with the recent 'plateauing' (i.e. slight relative decrease) of mean winter temperature in Switzerland and illustrates how important decadal variability is in understanding the trends in key snow indicators.

KEY WORDS new snow; snow fall; snow day; snow pack; reconstruction; climate change indicator; Switzerland; Alps; long series; decadal variability; trends; seasonal changes

Received 1 October 2010; Revised 17 December 2012; Accepted 19 December 2012

1. Introduction

Snow is a resource of utmost commercial (tourism, hydro-power) and social value (drinking water supply, hazards such as avalanches) for the Alpine region (Abegg *et al.*, 2007; Elsasser and Messerli, 2001). Snow climate indicators have been featured as one of the hallmarks in monitoring climate change in the IPCC reports (Lemke *et al.*, 2007) but also its relatively bad observational record has been stressed. It therefore is of great value to digitize, quality check and analyse as much data as possible that have been measured historically. Fortunately, Switzerland has a long history of snow monitoring and snow variability and trends have been analysed for different periods, some for the last 50 years (Beniston, 1997; Scherrer and Appenzeller, 2006; Scherrer *et al.*, 2004), some dating back to 1931 (Laternser and Schneebeli, 2003; Marty, 2008). All studies found a decrease of the Alpine snow pack since the mid 1980s especially at low stations (<1300 m asl, *cf* Laternser and Schneebeli, 2003) which was shown to be predominantly linked to an increase in local temperature (Scherrer *et al.*, 2004). This led to a discussion about the uniqueness of such a situation. There are no studies that analysed the development of the Swiss snow cover before 1931 and the question about the uniqueness of the snow scarcity in the Swiss Alps during the late 1980s remained unresolved to date. Wüthrich (2008) identified, digitized and quality checked hand written historical new snow measurements from the MeteoSwiss paper archive dating back to the second half of the 19th century (*cf* Figure 1). Of 12 series digitized, nine were found to be of sufficient quality for climatological trend analysis. This new data set allows to almost double the analysis time-range for new snow measurements from previously roughly 80 years to up to 145 years. To our knowledge, a snow analysis over such long time series is unique in Europe if not worldwide. In literature, we found analyses in Europe going back up to 125 years for Norway (Dyrrdal and Vikhamar-Schuler, 2009), ~70–90 years for northern Russia (Svyashchennikov and Førland, 2010), ~80 years for the Austrian Alps (Schöner *et al.*, 2009) and Bulgaria (Brown and Petkova, 2007) and ~50 years for the French Alps (Durand *et al.*, 2009).

---

* Correspondence to: S. C. Scherrer, Climate Division, Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland. E-mail: simon.scherrer@meteoswiss.ch

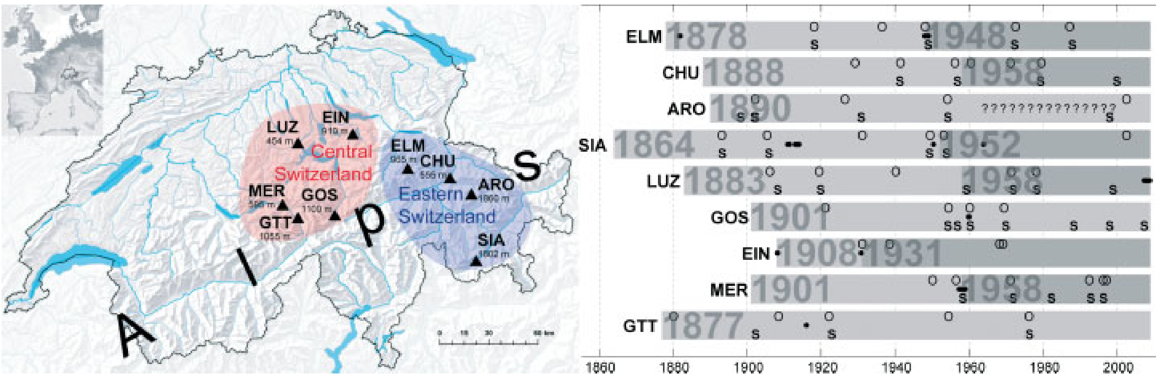


Figure 1. The geographical location and regionalization of the nine long snow series used in this study with station altitude (left) and meta information (right). Shown is the time period where the single stations measured new snow (light grey), snow depth (only if used in this study, dark grey), major observer changes (O), station relocations (S) and data gaps of 1 month or more (one filled black dot for every missing month). A period of different measurement practice in ARO is shown with '?' signs.

The aim of this article is to present an analysis of the snow variability in the Swiss Alps for the period 1864–2009 using the newly recovered new snow data together with the more extensive new snow and snow depth (SD) data set for the last 50–80 years. Derived snow climate indicator series based on new snow data are presented in order to better classify the recent low snow period in the late 1980s and 1990s (*cf* Scherrer *et al.*, 2004; Marty, 2008) and interannual to decadal Swiss Alpine snow variability in general. Indicators based on SD are of similar importance but since the newly digitized data is mostly new snow measurements, these had to be reconstructed using the new snow measurements, daily temperature and precipitation amounts available at the stations. We discuss how well and for which indicators this works well.

This article is structured as follows. First, the long data series, data treatment, limitations and methods used to reconstruct SD-based indicators are introduced in Section 2. The resulting indicator series suitable for climate analysis are presented in Section 3. New snow sum (NSS) and its derived variables maximum new snow (MAXNS) amounts and days with snowfall (DWSF) are discussed in Section 3.1. Reconstructed days with snow pack (DWSP) results for six stations are presented in Section 3.2. In Section 3.3., we shed light on the question whether the fraction of NSS and DWSP for autumn, winter and spring has changed over time. The NSS and DWSP trends from the long series are combined with trends from 71 additional snow stations measuring since at least the 1960s in Section 3.4. Finally, some conclusions and comments of more general scope are drawn in Section 4.

2. Data and methods

2.1. Snow data and data quality

Until recently the digital Swiss snow data available were restricted to the period after 1931 (*cf* Laternser and Schneebeli, 2003). Wüthrich (2008) identified handwritten station data from 12 stations in the MeteoSwiss paper archive for which the following three criteria were satisfied:

- original well readable data of daily NSS, SD or DWSP are available
- measurements started before 1910 and are still in operation today and
- the series contains not more than 5 years of continuous gap or not more than five gaps of 1 year length

The data of these 12 stations were digitized with great care and visual data quality checks were applied. It is well known that in order to analyse climate series with respect to variability and long-term trends they should be homogenized (Peterson *et al.*, 1998; Begert *et al.*, 2005). In our case, a rigorous homogenization process is not possible since the station network is extremely sparse and not enough information is available to create reference series for the homogenization procedure. To end up with reliable data suitable for climate analysis, we consulted the station metadata, i.e. the station history with information about the station characteristics such as station dislocations, observer changes and (a somewhat subjective) observer 'rating'. Normally, also changes in measurement techniques, instrumentation and the observation time need to be considered. This is not necessary in our case since the tools, i.e. the manual reading of a measuring rod for SD and new snow accumulated over a horizontal white chipboard, as well as the observation time did not change since the beginning of the monitoring in the 19th century. To qualify for further analysis three main criteria had to be satisfied by each station:

- the station experienced no station dislocation that was not within a 1 km of the original location (exposition was not considered explicitly)
- the vertical change of a station dislocation must be smaller than 100 m of altitude
- the metadata (as noted by the inspectors or data quality editors) indicates no severe 'irregularities' caused by

observer changes or the reliability of observers (see Wüthrich (2008) for details)

After applying these criteria, three series (Basel, Glarus and Säntis) had to be disqualified. The geographical features and the metadata (measurement begin, major observer changes, station relocations and data gaps) of the remaining nine series are presented in Figure 1. Possible unphysical features in the series that can be linked to the metadata are discussed in the Section 3. For more details about the data treatment and more metadata (also as tables) the reader is referred to Wüthrich (2008).

Unfortunately, the resulting set of nine series lacks stations from the southern slopes of the Alps, the Valais in south western Switzerland and the Jura mountain range in the west. To simplify the display of the results and to separate the main geographical locations, we define a '*central Switzerland*' group with the five stations Guttannen (GTT), Luzern (LUZ), Göschenen (GOS), Meiringen (MER) and Einsiedeln (EIN) and an '*eastern Switzerland*' group with the four stations Segl-Maria (SIA), Elm (ELM), Chur (CHU) and Arosa (ARO) shown in Figure 1.

2.2. New snow indicator construction, data gaps, smoothing

For engineering, construction, road maintenance purposes but also for climate change monitoring new snow indicators are of substantial interest. The following three new snow indicators have been computed from the observed daily new snow series for the nine stations on a seasonal to annual basis: (1) MAXNS, (2) NSS and (3) DWSF, defined here as days with NSS $\geq$ 1 cm. This is different from the definition in the SYNOP code (where already a visual recognition of snow flakes qualifies as day with snow fall). Due to the lack of documented eye-observations this definition is the only reasonable choice to make. With the exception of the two complete data series for CHU and ARO, the chosen new snow series have data gaps of 1–18 months in total (*cf* Figure 1). For the data display of smoothed tendency curves, these data gaps have been filled on a monthly basis using the average of the five preceding and five following years. In case one of the selected months has a gap itself, the averaging procedure was performed without this value. The original unsmoothed data have not been interpolated and the gaps remain visible. For the snow indicator construction, a 'snow year' has been defined from 1 September to 31 August of the following year. This special aggregation period (instead of e.g. the hydrological year) has been chosen since for higher stations, the first snow fall of the new snow year often takes place already in September. The year assigned to this 'snow year' is the year in which the period started, e.g. '1915' = 1 September 1915 to 31 August 1916. This is different to the year allocation for the hydrological year. To get a better feeling for the decadal variations in the data, 10 or 20 year Gaussian low pass filtered curves are added to the raw data series.

2.3. Reconstruction of snow depth indicators

Besides the new snow indicators introduced above, also SD indicators are of large value for climate monitoring purposes but also other applications such as construction, hazards, warnings and snow tourism. Indicators of interest are, e.g. SD and DWSP, i.e. days with SD above a certain limit, e.g. 1 cm (for road maintenance), 5 cm (for sledging) or 30 cm (for downhill skiing), *cf* e.g. OECD (2007). Since the SD measurements started only in the late 1950s for most stations (*cf* Figure 1), the SD indicators had to be reconstructed for the pre-measurement period.

2.3.1. *Methods*

To reconstruct SD, a snow model needs to be run in principle. There is a myriad of snow models in use today for very different purposes, e.g. in watershed modelling (Vehviläinen, 1992) or snow research (Bartelt and Lehning, 2002). In our case, only three input parameters are available at six stations (namely SIA, MER, CHU, ELM, LUZ and EIN): (1) new snow measurements, (2) daily mean temperature and (3) daily precipitation sums. We are thus forced to apply a very basic model. The Canadian Daily Snow Depth Database (Brown and Braaten, 1998) and the Water Balance Tabulations for Canadian Climate Stations (Johnstone and Louie, 1983) were created using such a method. The approach was found to give the best overall results in an evaluation of methods for reconstructing SD information from climatological data (Brown, 1996). It also worked reasonably well for a range of snow cover climates in northern America (Brown and Goodison, 1996; Scott *et al.*, 2003). There are no results showing whether the method works well in the complex terrain of the Swiss Alps. After introducing the method, we have to evaluate for which indicators the approach might be useful for climate analysis purposes.

The daily snow depth was calculated as follows:

$$\mathrm{SD}_t = \mathrm{SD}_{t-1} + \frac{1}{3}\mathrm{NS} - M \tag{1}$$

where SD is snow depth in cm; t, time in days; NS, the new snow sum in cm, M, the melt in cm and the snow settlement factor is taken 1/3. The melt M is defined according to the index method introduced by the US Army Corps of Engineers (1956):

$$M = k\left[\frac{9}{5}T\,(1.88 + 0.007R) + 1.27\right] \quad \forall \quad T > 0^{\circ}\mathrm{C} \tag{2}$$

where R is daily precipitation in cm and T daily mean temperature in °C. k is a local calibration factor that needs to be calibrated for each station separately.

The temperature values available in our case are measured 2 m above surface ($T_{2\mathrm{m}}$) according to WMO regulations. We found that the reconstruction was considerably better [root mean square error (RMSE) and mean absolute error (MAE) decrease of 28% for all days with SD > 0 cm] if we adapt the temperature limit to

$T_{2m} > 2\,^{\circ}\mathrm{C}$ instead of $T_{2m} > 0\,^{\circ}\mathrm{C}$. We therefore use the following slightly adapted formula for the melt contribution:

$$M = k\left[\frac{9}{5}T\,(1.88 + 0.007R) + 1.27\right] \quad \forall \quad T_{2m} > +2\,^{\circ}\mathrm{C} \tag{3}$$

2.3.2. *Data treatment*

The snow model needs daily input of mean temperature, precipitation sums and NSS. Snow and precipitation is measured around 7 am UTC, temperature on the other hand was measured three times a day (roughly at 7 am, 1 pm and 7 pm UTC) historically. The daily mean temperature used in this study was computed as the average of the 7 am, 1 pm and twice the 7 pm value. The double-count of the 7 pm value is to mimic the night temperature that was not explicitly measured. This procedure was also applied by other European weather services (e.g. the German Weather Service DWD, see their website) for the pre-automatic measurement period. A gap in the NSS measurement leads to a gap in the reconstructed SD series. An exception is when the precipitation data indicates that there is no precipitation in this period. In this case, the NSS is set to 0 cm. A temperature gap of 1 day was interpolated by the average of the preceding and the following day. A gap of several days leads to a gap in the reconstruction. Precipitation gaps of several days also lead to a gap in the reconstruction if daily mean temperature is $\geq +2\,^{\circ}\mathrm{C}$. For daily mean temperature $\leq +2\,^{\circ}\mathrm{C}$, precipitation gaps were filled with 0 cm, since there is no influence on the reconstruction (*cf* melt Equation (3)).

2.3.3. *Method calibration and validation*

2.3.3.1. General remarks: The k value in the melt formula remains the only 'tuneable' parameter in the above SD reconstruction procedure if the settling factor 1/3 is taken as constant (as published). For each station, one k value was calibrated using daily data of the odd years from 1959 to 2007. The data from the even years between 1960 and 2008 were used to validate the results. Table 1 shows the k values (range: 0.25–0.42) based on minimizing MAE and RMSE of the reconstructed and observed daily data with SD $\geq$ 0 cm. MAE and RMSE criteria lead to basically the same k values (differences < 0.01). The resulting k but also the MAE/RMSE calibration/validation values vary considerably between stations. k is normally smaller for low (snow poor) stations (e.g. $k = 0.25$ for LUZ and CHU) than for higher (snow rich) stations ($k \sim 0.4$). This indicates that for the same T and R values in Equation (2), the melt M is larger at higher stations. The reason for these differences is that Equation (2) neglects other important melt 'drivers' such as radiation, humidity and wind effects which therefore map onto k and increase k. Especially for wind and radiation effects this makes sense since higher stations are often exposed to more wind and radiation. Factors not related to melt, such as snow erosion, wind-drift, precipitation undercatch and a non-constant settling factor might also map onto the factor k. Note also that the MAE/RMSE values are much larger for snow rich stations. This can be expected since the absolute amounts are also much higher.

Table 1. Melt calibration factors k, daily mean absolute error (MAE in cm) and daily root mean squared error (RMSE in cm) for days with snow depth $\geq$1 cm at all stations where snow depth was reconstructed in the calibration (odd years between 1959 and 2007) and validation (even years between 1960 and 2008) period.

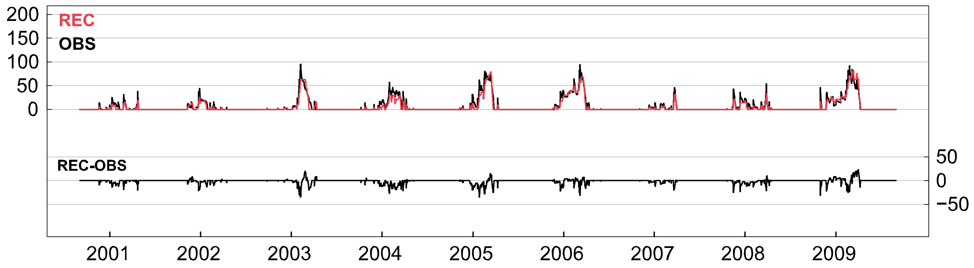
Station	k	MAE (cm)		RMSE (cm)	
		Calib.	Valid.	Calib.	Valid.
LUZ (454 m)	0.25	0.5	0.5	1.9	2.0
CHU (555 m)	0.25	0.9	1.1	3.3	7.8
MER (595 m)	0.36	1.1	2.0	3.3	6.0
EIN (910 m)	0.42	3.0	3.0	7.1	7.2
ELM (965 m)	0.40	5.3	5.4	11.9	12.4
SIA (1802 m)	0.41	11.8	12.1	21.2	21.8

2.3.3.2. Snow depth: The performance of the SD reconstruction is evaluated for a low altitude (EIN, 910 m asl) and a high altitude station (SIA, 1802 m asl) in more detail. Figure 2 compares the reconstructed SD with observed SD for the 10-year period September 2000 to August 2009 using the calibrated k value from the odd years 1959–2007. The SD evolution over the snow year is reasonably well captured, especially for the lower altitude station EIN. Some key numbers on the performance on a daily scale for all stations are given in Table 1.

The method has problems to reach the observed SD maxima (especially in autumn). A potential reason is that the constant snow settlement factor leads to problems especially for snow fall events that last several days. SD maxima are also often underestimated for isolated snowfall cases in spring, summer and autumn since the settlement factor is high and the mean temperature leads to very large melt M. As a consequence, the fallen snow is melted quickly and hardly any SD is modelled for the following days.

Another problematic feature is found for high altitude stations which exhibit a permanent snow cover over several months. Here, the reconstruction often underestimates SD in the early season and overestimates SD substantially in the melt period in spring (*cf* Figure 2(b)). This can in part be attributed to increased solar radiation in spring, which our simple model does not account for. Very similar results were documented for stations in southern Ontario (*cf* Figure 3 in Scott *et al.*, 2003). For low altitude stations the reconstruction bias is less dependent on season but overall still negative (*cf* Figure 2(a)). In this case, poor SD representation might be just linked to the poor representation of maxima especially for several day snowfall events mentioned above. In total, the reconstructed daily SD values for low and high altitude

(a) **Einsiedeln (910 m asl)**



(b) **Segl-Maria (1802 m asl)**

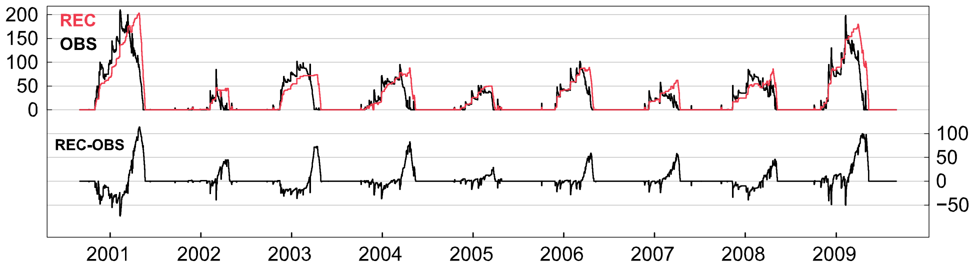


Figure 2. Comparison of reconstructed (REC, red) and observed (OBS, black) snow depth as well as the reconstructed minus observed (REC−OBS) values for Einsiedeln 910 m asl (panel a) and Segl-Maria 1802 m asl (panel b) from September 2001 to August 2009. Units: cm.

stations are underestimated in over 75% of the days with snow and overestimated in less than 25% of the days with snow.

The seasonal cycle of SD is rather well captured at low altitude stations and shows some problems at high altitude stations. Since there are concerns regarding the tendency to underestimate extreme SD on a daily scale and as a consequence also mean SD values, we refrain from creating an annual SD mean/sum indicator for the reconstruction period. In the next section, we check whether indicators for DWSP can be reconstructed with a useful accuracy for climate analysis.

2.3.3.3. *Days with snow pack:* Figure 3 shows reconstructed DWSP for two limits (SD $\geq$ 1 cm and SD $\geq$ 30 cm) at the station EIN. We assess the performance not only for the validation period (even years from 1960 to 2008) but also for the completely independent reconstruction period between 1931 and 1958 for which SD measurements are available but the method has no knowledge of. For calibration, the odd years between 1959 and 2007 are used. The 1931–1958 values are on average underestimated by ∼14.5 d per year or ∼13% with respect to observation for the 1 cm limit and by ∼25.5 d per year or ∼55% for the 30 cm limit. The results are better for the validation period (even years from 1960 to 2008) with values underestimated by ∼8.3 d per year or 7% for 1 cm and ∼10.5 d per year or 21.5% for 30 cm. Since the errors to reconstruct skiable days (DWSP $\geq$ 30 cm) are up to 55% for the independent reconstruction period (e.g. in 1939 only one DWSP $\geq$ 30 cm is modelled although 71 DWSP were observed), we think that a reconstruction makes sense only for DWSP $\geq$ 1 cm where the daily reconstruction errors are in the order of 10%.

The new snow and SD indicators discussed in the next section are thus limited to (1) MAXNS, (2) NSS, (3) DWSF and (4) DWSP $\geq$ 1 cm.

3. Results

3.1. New snow indicators

3.1.1. *Maximum new snow*

Figure 4 shows the evolution of MAXNS for the nine long series introduced above. For the lower altitude stations, the mean MAXNS ranges between 15 and 25 cm d^{-1}, for medium altitude stations the range is between 25 and 35 cm and for high altitude stations values between 35 and 60 cm are found. The absolute daily extremes in the data set are 1 cm (LUZ, 1989) and 110 cm (GOS, 1981). There are no significant trends considering the whole measuring period but some decadal variations can be identified. For most stations somewhat higher MAXNS are found between 1910 and 1920 as well as between 1970 and 1985. There seems to be a minimum around 1930. Note that for the most recent period since the late 1980s the mean MAXNS values (smoothed curves) are not particularly low. It is, however, striking that since the year 2000, no extremely large values (e.g. MAXNS > 60 cm) are found any more. This is directly linked to a lack in weather situations that lead to extreme winter precipitation in the same period which is likely to be linked to natural decadal variability. The influence of station relocations and observer changes (*cf* Figure 1) seems to be negligible.

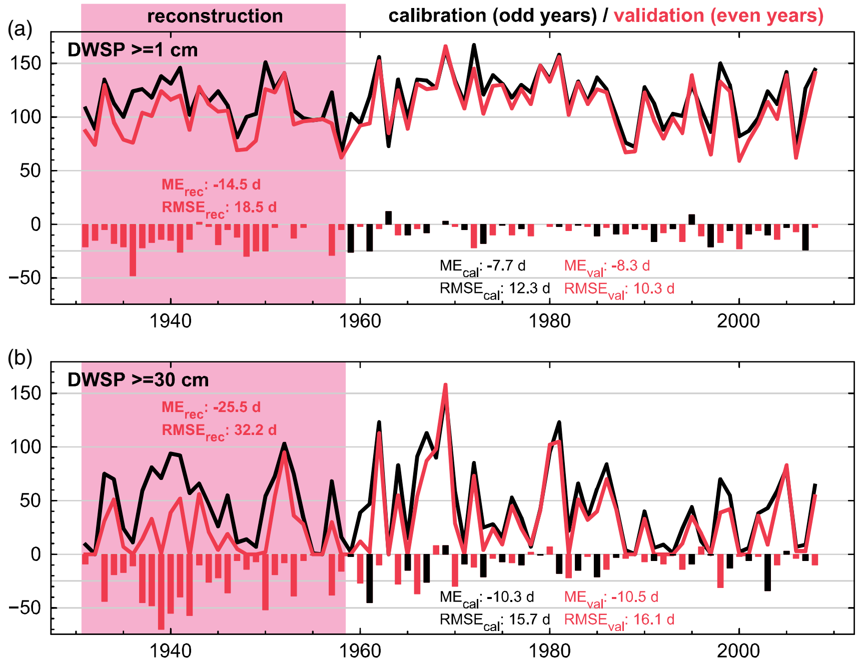


Figure 3. Days with snow pack (DWSP) ≥1 cm (panel a) and ≥30 cm (panel b) per snow year for Einsiedeln during the period 1931–2008. The observed DWSP are shown as black line, the reconstructed DWSP as red line. The reconstructed minus observed DWSP are shown as bar graphs. Model calibration period (cal): odd years between 1959 and 2007, validation period (val): even years between 1960 and 2008. 1931–1958 (red shading) is reconstructed using the parameter estimate from the calibration period only. Mean error (ME) and root mean square errors (RMSE) for the calibration, validation and reconstruction period are also reported.

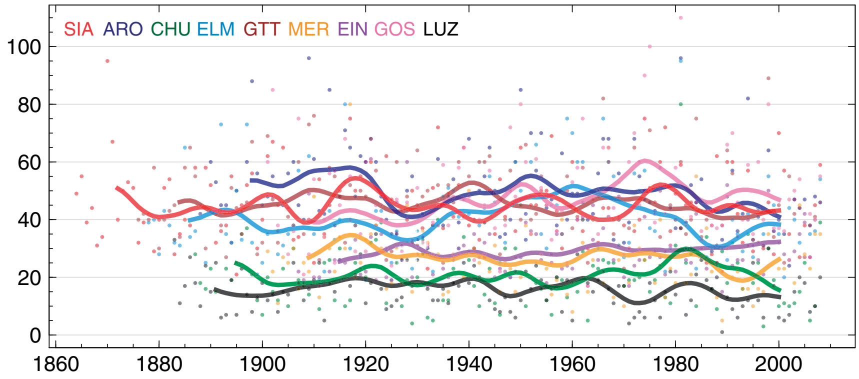


Figure 4. Maximum new snow (MAXNS) (cm) per snow year (coloured points). The 20-year Gaussian smoothed estimate is shown as line. For station colour coding, see top left corner.

3.1.2. New snow sums

Figure 5 depicts the evolution of annual NSS values for the eastern (left panel) and central Switzerland (right panel). The most obvious feature of the series is their large interannual variability which in general increases with station altitude. The NSS values are highly dependent on station altitude and range from 1 cm (LUZ, 1989) to 12.86 m (ARO, 1974). There is also considerable decadal variability. All stations show lower NSS values since the late 1980s (*cf* also Scherrer *et al.*, 2004 and Marty, 2008). For most low altitude stations (LUZ, CHU, MER, EIN, GTT) these values are unrivalled since the beginning of the measurements. For higher stations the values are at least among the lowest measured since the late 19th century. Most stations show a phase of high NSS in the 1970s and early 1980s. Especially for central Switzerland this maximum is very clear and seems to start rather abruptly already in the 1960s (Figure 5, right panel). The 1930s, 1940s and 1950s were a period of lower NSS. There is an indication for higher NSS between 1900 and 1920. In general, the consistency between stations is smaller in the eastern part. This is not surprising since the station locations and expositions are very different from each other (e.g. ELM and SIA are influenced by very different flow patterns). The station SIA shows very strong decadal fluctuations. Whether these fluctuations can be attributed to climatology only is difficult to assess since we have no other station data available that is that highly influenced by the climate of the southern slopes of the Alps. Using the metadata alone (i.e. the four minor station relocations and six observer changes documented in Figure 1) the strong fluctuations cannot be explained to a reasonable degree. The same applies to the other stations. We therefore assume that the fluctuations shown are mainly of climatological nature.

3.1.3. Days with snow fall

Figure 6 depicts the evolution of another important new snow measurement indicator, the number of DWSF. The evolution is very similar to the NSS evolution (*cf* Figure 5), which shows that the NSS variability is strongly linked to the DWSF. In absolute numbers, the relation highly depends on the station: GOS, EIN and GTT show almost the same number of DWSF with a double maximum in the 1960s and around 1980s but quite different NSS. This indicates that most snow events are shared (snow at station A means also snow at station B) but the actual amount is highly dependent on station location and exposition. As for NSS, SIA shows very strong multi-decadal fluctuations with minima from 1890 to 1910, the late 1930s to 1950s and since the late 1980s. Maxima are found for the 1910s to 1930s (peaking around 1915) and in the 1970s and early 1980s. The very early period from 1864 to 1880 shows average behaviour. In contrast to most other stations and the NSS, the low SIA values from 1890 to 1910 and in the late 1930s to 1950s are even lower than the ones found since the late 1980s. Also for this indicator, the metadata do not help to explain the different behaviour of SIA and we assume that the series is representing the climatological properties of the southerly influenced part of the Swiss Alps. For ARO, significant almost linear increases are found for the period between 1930 and 1980. The metadata indicates that between the mid-1960s and at least into the late 1980s the SD measurements have been taken at another snow stake every year from mid-April into the summer. Although the note reassures that the new snow measurement (which is the only parameter needed to compute DWSP) has always been taken at the same spot, we need to be cautious whether these changes are really linked to climatology.

3.2. Days with snow pack reconstructions

In this section, we discuss the results of the reconstructed DWSP $\geq$ 1 cm for six long series. Figure 7 shows the results for the reconstruction period (thin lines) as well as the period where SD has been actually measured (thick lines). As already discussed in Section 2.3., the results in the 1960–2008 validation period show reasonable performance (*cf* the thin/thick lines in Figure 7). This gives us an indication that the reconstruction is of useful accuracy especially for investigating decadal fluctuations. There is considerable decadal variability in the reconstructed data set which shows similarities with the DWSF and the NSS discussed above (*cf* Figures 5 and 6). A DWSP maximum is found from the 1960s to the early 1980s (especially well visible in the eastern Switzerland series, Figure 7 right panel). The data also indicates that for most stations (LUZ, CHU, MER, ELM, SIA) the DWSP in the late 1980s and 1990s have been the lowest since the start of the observations almost 150 years ago. Since the reconstruction method tends to underestimate DWSP (*cf* Figure 3) this statement can be made with some confidence. Note that the data also show some indications for a trend reversal and values above the lowest levels found in the late 1980s and 1990s. This fact is elaborated with many more stations in Section 3.4.

3.3. Changes in the seasonal distribution of snow pack

From simple global warming arguments and climate model results one might expect that changes in snow pack values are especially large at the beginning or the end of the snow season, in other words, there might be pronounced changes in the seasonal distribution of snow cover accumulation. To see whether any significant changes can be found in our data, Figure 8 depicts the NSS and DWSP fractions (with respect to the yearly values) for autumn (SON), winter (DJF) and spring (MAM) at three stations with different altitude (low: LUZ 454 m asl; medium: ELM 965 m asl and high: SIA 1802 m asl). As expected, the average fractions change with altitude. While the spring NSS fraction is about 20% for the low altitude station, it is roughly 40% for the high altitude station. For winter, the NSS fraction changes from over 70% for the low altitude station to less than 40% for the high altitude station. In autumn finally, the low altitude station NSS fraction is mostly less than 10% but up to 20% for the high altitude station. Roughly, similar results are found for DWSP. There is considerable decadal variability (especially for NSS) and hardly any trends over the whole time period are visible by eye except maybe a slight decrease of the MAM fraction at the station LUZ.

Table 2 gives more objective numbers in terms of the fraction changes using ordinary linear least-square regression trends applied to the 10 year Gaussian low pass filtered data. Significant NSS decreases are found for all stations in spring (MAM). The fraction decrease is largest and significant ($p < 0.001$) for the lowest station LUZ with about 7% per century. For ELM and SIA the decrease are 3% ($p = 0.02$) and 4% per century ($p = 0.008$), respectively. These results are in line with the results presented by Laternser and Schneebeli (2003). There are also NSS fraction increases in autumn (SON) for LUZ and winter (DJF) for SIA. Note that these trends might be spurious since we work with fractions and the three seasons have to add up to one. As a consequence, a real trend needs to be compensated by a spurious trend in one of several of the other seasons.

For fractional changes in DWSP the decreases in spring are only significant for SIA ($p = 0.001$) together with slight increases in winter ($p < 0.001$). Increases are also found for LUZ in autumn ($p < 0.001$). Whether all these fractional DWSP trends are real or in part compensation effects is hard to say. Since the visual inspection did not reveal clear changes, we tend to interpret these trends partially as compensation effects instead of real trends.

We repeated the fraction change analysis for the last 50 years (1960–2009) where climate change became

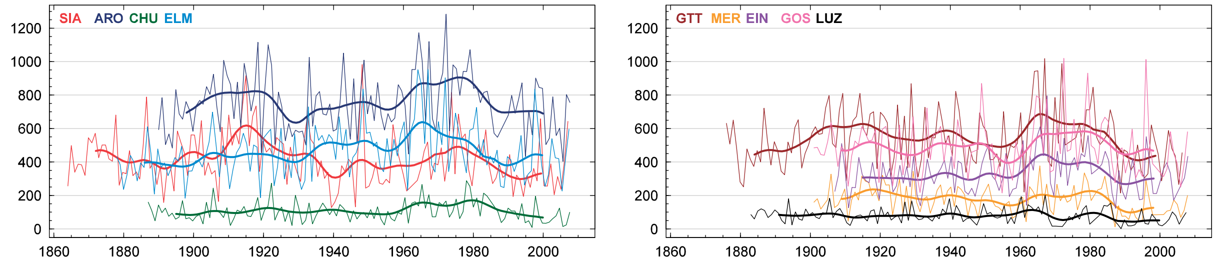


Figure 5. New snow sums (NSS) in (cm) per snow year. Left panel: Eastern Switzerland stations, right panel: Central Switzerland stations.

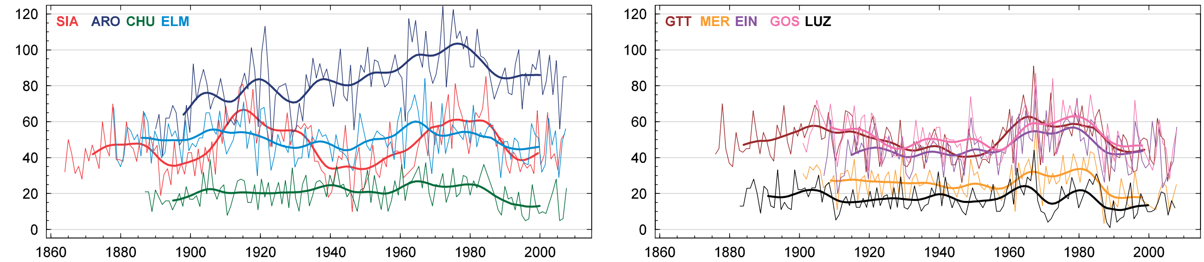


Figure 6. Number of days with snow fall (DWSF) per snow year. Left panel: Eastern Switzerland stations, right panel: Central Switzerland stations.

most obvious. The results are qualitatively similar but there are even stronger spring fraction declines at the low station LUZ (26% instead of 7% per century) and medium station ELM (8% instead of 3% per century). This decrease in spring fraction seems reasonable as several studies (e.g. using phenology) showed that spring begins earlier in the last decades (Menzel and Fabian, 1999; Studer *et al.*, 2005). Similar to our results, we find no signs for a later onset of snow pack in the literature (Laternser and Schneebeli, 2003).

In contrast to the study by Schöner *et al.* (2009), which found a decrease of the core winter (DJF) fraction for some high altitude stations in the Austrian Alps, no clear winter changes are found in the Swiss Alpine series. Note that the Austrian stations to which the above statement applies are higher (2400–3100 m asl) than the stations analysed in this study and results cannot directly be compared.

3.4. Trend analysis: combining the long series with other snow observations

To put the new long series trend results in context with results from other snow observations and with previous trend analysis of Swiss stations published by Scherrer *et al.* (2004), we present an adapted version of their Figure 2. The new version (our Figure 9) allows extending the time window considered in Scherrer *et al.* (2004) from about 40 years (1958–1999) to more than 100 years (the late 19th century to 2009) although not for all stations. We present relative and absolute 20 year running mean linear least-square trends for yearly NSS and DWSP for the long series together with 71 additional quality checked MeteoSwiss snow stations of differing altitudes.

All four panels indicate large decadal variability with phases of increasing (blue) and decreasing (red) trends. The trend phases often are similar for all altitudes, e.g. increases are found between 1960 and 1980 for most stations. The most distinct feature in all four panels is the strongly decreasing trends in the late 1980s and 1990s. The trend amplitudes are unprecedented since the beginning of records in the later 19th century. The relative decreases are larger for low than for high altitudes. This is especially the case for DWSP with trends larger than −75% per 10 years in the 1990s at low altitudes (<600 m asl) compared to trends mostly less than −25% per 10 years at higher altitude (Figure 9(b)). Also for NSS larger trends are found for low altitudes (order −75% per 10 years) than high altitudes (order −25 to −50% per 10 years), thus the differences are somewhat smaller than for DWSP (*cf* Figure 9(a)). For the absolute decreases the differences between altitudes are less pronounced (panels c and d). Except for very low stations (<300 m asl) absolute DWSP trends are of similar magnitude. For NSS, the absolute trends are very similar for altitudes above ∼700 m asl and somewhat smaller for lower stations.

The strongly decreasing trends in the late 1980s and 1990s are followed by a trend reversal in most recent times (2000–2009). This is especially obvious for stations below 800 m asl (Figure 9, all panels). Since at low altitudes the snow pack is temperature limited (see Scherrer *et al.*, 2004) this trend reversal seems to be linked to the ‘plateauing’ or even slightly decreasing temperature in Switzerland. Figure 10 shows the absolute mean winter (DJF) temperatures for three different altitude bands (400–500 m asl, 700–800 m asl and 1000–1100 m asl) in the period 1961–2010 using the gridded 2 km temperature data set introduced in Ceppi *et al.* (2012). It

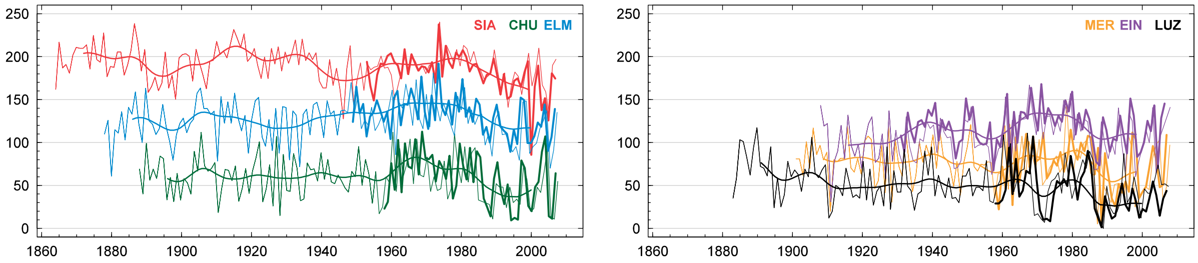


Figure 7. Observed (bold line) and reconstructed (thin line) days with snow pack DWSP (snow depth ≥ 1 cm) per snow year for six stations.

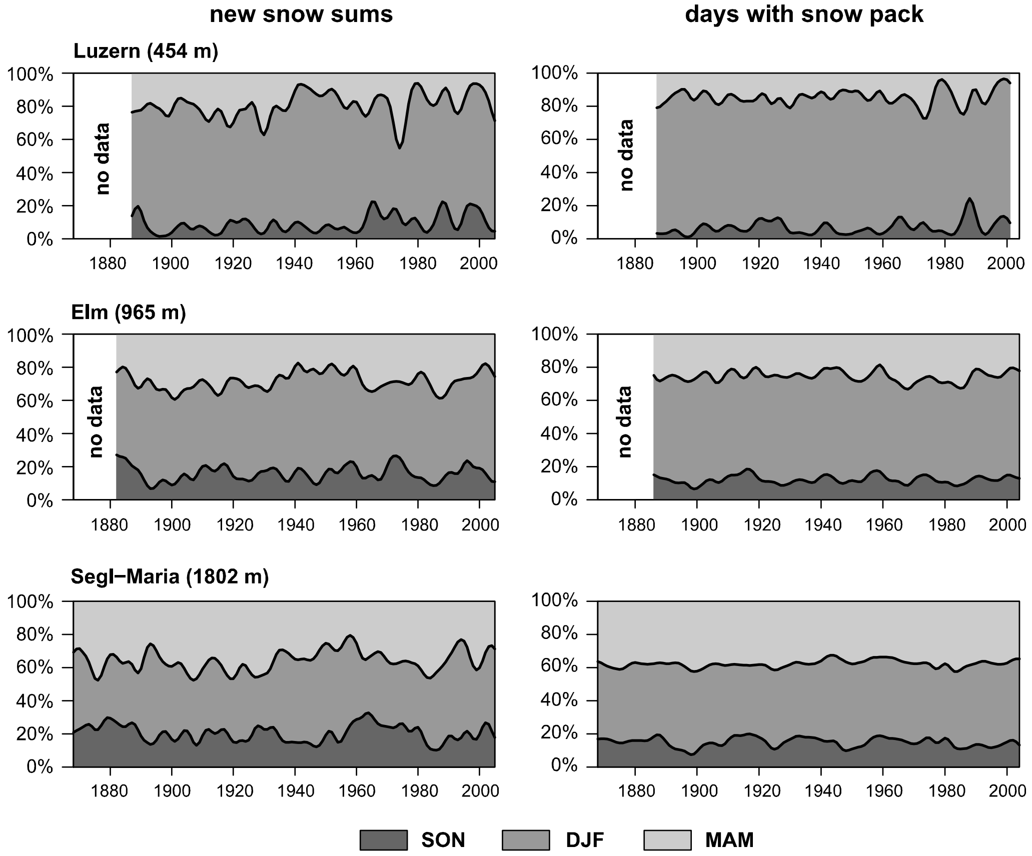


Figure 8. Percentage fraction of cumulated seasonal new snow sums (NSS, left panels) and days with snow pack DWSP ≥1 cm (right panels) for the three meteorological seasons SON (dark grey), DJF (grey) and MAM (light grey) and three stations of different altitude (LUZ 454 m, top; ELM 965 m, middle and SIA 1802 m, bottom). The curves are 10-year Gaussian smoothed.

shows that DJF temperatures have generally increased from values somewhat below 0 °C in the 1960s to values around or above 0 °C in the more recent time. The closeness of the lower Swiss regions to the 0 °C isotherm makes the snow evolution very temperature dependent (*cf* also Scherrer *et al.*, 2004) and changes in the temperature evolution can have quite strong effects on snow indicators. The two phases with relative temperature increases (roughly 1960–1975 and 1985–2000) are associated with relative snow pack decreases (*cf* Figure 9) with the strongest relative decreases in the late 1980s and 1990s coinciding with the strong temperature increases and high temperature levels. The snow increases in the late 1970s and early 1980s as well as after the year 2000 go in hand with relative temperature declines (*cf* Figure 10). The weak declines after the year 2000 started from high temperature levels, whereas stronger temperature declines from medium temperature levels are found in the late 1970s and early 1980s. As a consequence, the snow ‘recovery’ is relatively weak in the period 2000–2009 and stronger in late 1970s and early 1980s. All this illustrates how important decadal variability and the 0 °C isotherm location are in understanding changes in key snow indicators and that trends signs can even be reversed due to decadal variability superimposed on ongoing climate change.

4. Conclusions

In this study, we presented an analysis of the snow variability in the Swiss Alps for the period 1864–2009 using

Table 2. Cumulated new snow sums (NSS) and days with snow pack (DWSP) fraction change per century for the period 1864–2008 at the three stations Luzern (LUZ), Elm (ELM) and Segl-Maria (SIA) using ordinary least-square regression.

	SON		DJF		MAM	
	NSS	DWSP	NSS	DWSP	NSS	DWSP
LUZ	**0.06 ($p < 0.001$)**	**0.04 ($p < 0.001$)**	<0.01 ($p = 0.73$)	−0.02 ($p = 0.31$)	**−0.07 ($p < 0.001$)**	−0.02 ($p = 0.09$)
ELM	<0.01 ($p = 0.72$)	<0.01 ($p = 0.36$)	0.03 ($p = 0.07$)	−0.01 ($p = 0.11$)	**−0.03 ($p = 0.02$)**	<0.01 ($p = 0.53$)
SIA	−0.02 ($p = 0.14$)	<0.01 ($p = 0.16$)	**0.05 ($p = 0.001$)**	**0.02 ($p < 0.001$)**	**−0.04 ($p = 0.008$)**	**−0.01 ($p = 0.001$)**

Significant trends (p-values <0.05) (low pass smoothed curve shown in Figure 8) are shown in bold. Since the fractions add up to 1, a trend in one season is compensated by the two other seasons in the opposite direction.

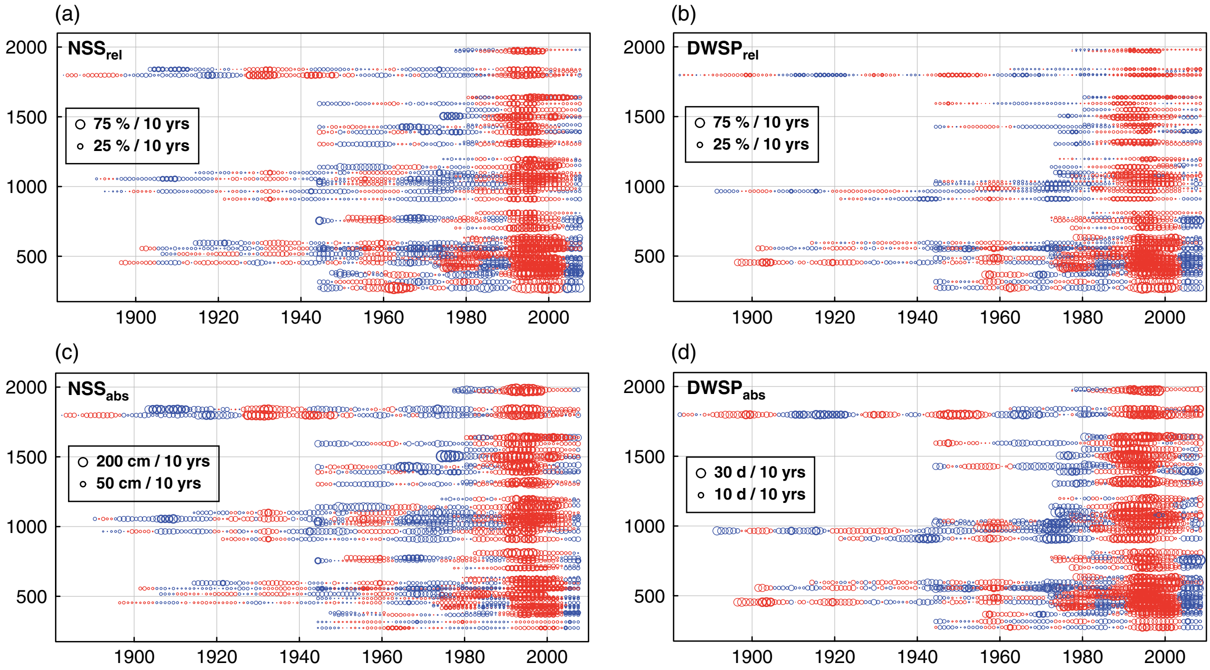


Figure 9. Twenty-year running window trends of new snow sum (NSS, left panels) and days with snow pack (DWSP, right panels) ≥ 1 cm. Trends are shown against station altitude (m asl) at the end year of the corresponding 20-year period (i.e., in 2008 for the period 1989–2008). Blue (red) circles show positive (negative) trends. Significant trends (two-sided t-test, 5% level) are shown in bold. A scale for the circles is shown in all panels. Upper panels: relative trends in percent per 10 years with respect to the mean value of the period 1961–1990. Lower panels: absolute trends in cm per 10 years (NSS) and days per 10 years (DWSP).

nine newly digitized daily new snow series from different altitudes (450–1860 m asl) and a more extensive new snow and SD data set for the last 50–80 years. A strict homogenization of the new snow series was not possible but the metadata (i.e. station relocations, observer changes etc.) of the new snow data showed no indications for serious unphysical breaks in the analysed series. Important snow climate indicators such as NSS, MAXNS and DWSF have been computed. Another important indicator, the DWSP ≥ 1 cm is constructed with useful accuracy for six stations using reconstructed SD based on the slightly adapted version of the Brown and Braaten (1998) method. The reconstructed daily SD values themselves tend to be biased substantially especially for large SDs, high stations and towards the end of the snow season and are therefore of limited value for climatological trend analysis. Reconstructed SD indicators with high SD limits (e.g. skiable days, i.e. DWSP ≥ 30 cm) suffer from large errors up to 55% for DWSP at the station EIN from 1931 to 1958.

The analysis of the new snow indicators shows large decadal variability with phases of low and high values for NSS, DWSF and DWSP. For low stations NSS, DWSF and DWSP show the lowest values recorded in the late 1980s and 1990s. For higher stations the values of late 1980s and 1990s are at least among the lowest since the late 19th century. A combination of the new long series with 71 stations measuring at least since the 1960s confirmed that the magnitude of the declines in the late 1980s and 1990s were unprecedented for all altitudes in the last 145 years. For MAXNS amounts, however, no clear trends and smaller decadal variability are found, although very large MAXNS values (>60 cm) are not found since the year 2000. The fraction of NSS and DWSP in different seasons (autumn, winter and spring) has changed only slightly over the last roughly 150 years. Some decreases attributable to temperature changes are found for spring, especially for NSS at low stations. No clear changes are found for other seasons. Presumably caused by natural decadal variability

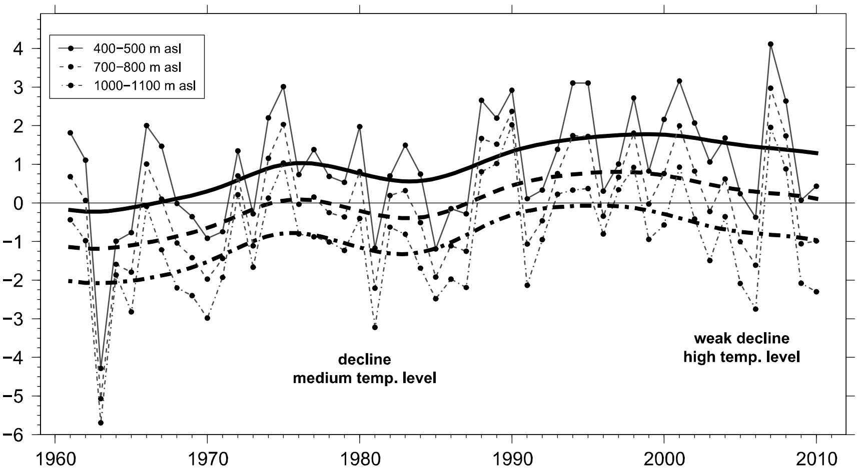


Figure 10. Mean winter (DJF) temperatures (°C) for the period 1961–2010 at three different altitude bands (400–500 m asl: solid line; 700–800 m asl: dashed and 1000–1100 m asl: dash-dotted). Shown are yearly values as well as a smoothed estimate using a Nadaraya–Watson normal kernel regression smoother with a bandwidth matching a 20-year Gaussian low pass filter. The database is 2 km gridded temperature (*cf* Ceppi et al., 2012).

superimposing ongoing climate change, the NSS and DWSP indicator trends reversed after the year 2000 at low and medium altitudes. This trend reversal is consistent with the recent plateauing and slight decreases of winter temperature in Switzerland and illustrates how important decadal variability is in understanding the trends in key snow indicators.

This study has shown that there are changes in the Swiss Alpine snow pack which are indicative for climate change (especially increasing temperature). Nevertheless, the complex local influences on the snow pack via temperature, precipitation, radiation, wind and humidity and the large decadal variability in the mid-latitude climate system makes it difficult to understand the details of changes in Swiss Alpine snow pack. This fact stresses the need for continued high density monitoring of Swiss Alpine snow pack, more analysis to get a better understanding of the physical processes affecting snow and finally developing better physically based models to project the future of Swiss Alpine snow pack.

Acknowledgments

The authors thank Paulo Ceppi for producing Figure 8, the referees for their valuable suggestions and all MeteoSwiss observers for manually measuring snow every morning, some of them since more than 50 years!

References

Abegg B, Agrawala S, Crick F, de Montfalcon A. 2007. Climate change impacts and adaptation in winter tourism. *Climate Change in the European Alps*. S. Agrawala. Paris, OECD: 25–60. ISBN: 92-64-03168-5.

Bartelt P, Lehning M. 2002. A physical SNOWPACK model for the Swiss avalanche warning Part I: numerical model. *Cold Regions Science and Technology* **35**(3): 123–145.

Begert M, Schlegel T, Kirchhofer W. 2005. Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. *International Journal of Climatology* **25**: 65–80.

Beniston M. 1997. Variatons of snow depth and duration in the Swiss Alps over the last 50 years: Links to changes in large-scale climatic forcings. *Climatic Change* **36**: 281–300.

Brown RD. 1996. Evaluation of methods for climatological reconstruction of snow depth and snow cover duration at Canadian meteorological stations. In Proceedings of 53rd East. Snow Conference, 1–3 May 1996, Williamsburgh, Virginia, 55–65.

Brown RD, Braaten RO. 1998. Spatial and temporal variability of Canadian monthly snow depths, 1946–1995. *Atmosphere-Ocean* **36**(1): 37–54.

Brown RD, Goodison B. 1996. Interannual variability in reconstructed Canadian snow cover, 1915–1992. *Journal of Climate* **9**: 1299–1318.

Brown RD, Petkova N. 2007. Snow cover variability in Bulgarian mountainous regions, 1931–2000. *International Journal of Climatology* **27**(9): 1215–1229.

Ceppi P, Scherrer SC, Fischer AM, Appenzeller C. 2012. Revisiting Swiss temperature trends 1959–2008. *International Journal of Climatology* **32**: 203–213. DOI: 10.1002/joc.2260

Durand Y, Giraud G, Laternser M, Etchevers P, Lesaffre B, Merindol L. 2009. Reanalysis of 47 years of climate in the French Alps (1958–2005): climatology and trends for snow cover. *Journal of Applied Meteorology and Climatology* **48**(12): 2487–2512.

Dyrrdal A, Vikhamar-Schuler D. 2009. Analysis of long-term snow series at selected stations in Norway. met.no report 05/2009 Climate. 82.

Elsasser H, Messerli P. 2001. The vulnerability of the snow industry in the Swiss Alps. *Mountain Research and Development* **21**: 335–339.

Johnstone K, Louie P. 1983. Water balance for Canadian climate stations. Atmospheric Environment Service Report#8–83. Downsview, Ontario, Canada.

Laternser M, Schneebeli M. 2003. Long-term snow climate trends of the Swiss Alps (1931–99). *International Journal of Climatology* **23**(7): 733–750. DOI: 10.1002/joc.912

Lemke P, Ren J, Alley RB, Allison I, Carrasco J, Flato G, Fujii Y, Kaser G, Mote P, Thomas RH, Zhang T. 2007. Observations: changes in snow, ice and frozen ground. In *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, UK/New York.

Marty C. 2008. Regime shift of snow days in Switzerland. *Geophysical Research Letters* **35**: L12501. DOI: 10.1029/2008GL033998

Menzel A, Fabian P. 1999. Growing season extended in Europe. *Nature* **397**: 659.

OECD. 2007. Climate change in the European Alps. Agrawala S (ed). ISBN: 92-64-03168-5. 136.

Peterson TC, Easterling DR, Karl TR, Groisman P, Nicholls N, Plummer N, Torok S, Auer I, Boehm R, Gullett D. 1998. Homogeneity adjustments of in situ atmospheric climate data: A review. *International Journal of Climatology* **18**: 1493–1517.

Scott D, McBoyle G, Mills B. 2003. Climate change and the skiing industry in Southern Ontario. (Canada): exploring the importance of snowmaking as a technical adaptation. *Climate Research* **23**: 171–181.

Scherrer SC, Appenzeller C. 2006. Swiss Alpine snow pack variability: major patterns and links to local climate and large-scale flow. *Climate Research* **32**(3): 187–199.

Scherrer SC, Appenzeller C, Laternser M. 2004. Trends in Swiss Alpine snow days: the role of local- and large-scale climate variability. *Geophysical Research Letters* **31**: L13215. DOI: 10.1029/2004GL020255

Schöner W, Auer I, Böhm R. 2009. Long term trend of snow depth at Sonnblick (Austrian Alps) and its relation to climate change. *Hydrological Processes* **23**(7): 1052–1063.

Studer S, Appenzeller C, Defila C. 2005. Inter-annual variability and decadal trends in alpine spring phenology: a multivariate analysis approach. *Climatic Change* **73**: 395–414.

Svyashchennikov PN, Førland EJ. 2010. Long-term trends in temperature, precipitation and snow conditions in Northern Russia. met.no report 9/2010 Climate. 32.

US Army Corps of Engineers. 1956. Snow hydrology. US Army Corps of Engineers, Portland, OR.

Vehviläinen B. 1992. Snow cover models in operational watershed forecasting; Yhteenveto: Lumimallit vesistöjen ennustemalleissa. In *Publications of the Water and Environment Research Institute 11*, National Board of Waters and the Environment: Helsinki.

Wüthrich C. 2008. *Lange Schneemessreihen der Schweiz*. Geographisches Institut Universität Bern und MeteoSchweiz Zürich, Diploma thesis, 102, (in German).