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Regime shift of snow days in Switzerland

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[1] The number of days with a snow depth above a certain threshold is the key factor for winter tourism in an Alpine country like Switzerland. An investigation of 34 long-term stations between 200 and 1800 m asl (above sea level) going back for at least the last 60 years (1948–2007) shows an unprecedented series of low snow winters in the last 20 years. The signal is uniform despite high regional differences. A shift detection analysis revealed a significant step-like decrease in snow days at the end of the 1980's with no clear trend since then. This abrupt change resulted in a loss of 20% to 60% of the total snow days. The stepwise increase of the mean winter temperature at the end of the 1980's and its close correlation with the snow day anomalies corroborate the sensitivity of the mid-latitude winter to the climate change induced temperature increase. **Citation:** Marty, C. (2008), Regime shift of snow days in Switzerland, *Geophys. Res. Lett.*, *35*, L12501, doi:10.1029/2008GL033998.

1. Introduction

[2] Snow influences life and society in an Alpine country like Switzerland in many ways. The amount and duration of snow in the Alps has a high economic significance in terms of tourism and hydropower. Many Alpine towns and villages heavily depend on snow, because their economy is dominated up to 90% by winter tourism [*Abegg et al.*, 2007]. The vast majority of customers of such ski areas live in the pre-alpine regions of Switzerland, Austria, Germany and Italy. A longer sequence of almost snowless winters in these regions, as was observed between the late 1980's and mid 1990's led to the discussion about the uniqueness of such a situation. The possible connection to climate change initiated quite a few papers [*Beniston*, 1997; *Laternser and Schneebeli*, 2003; *Scherrer et al.*, 2004], which investigated the past variability and trends. All these studies found a decrease of the snow depth since the mid 1980's for low-lying stations. *Beniston* [1997] stated that there have been earlier periods in the records where snow depth was as low as during the late 1980's. The general decline of snow at low-lying stations could be linked to anomalous warm winter temperatures since the mid 1980's. This increase of temperatures could be associated with the longest observed period with a strong, persistent, positive North Atlantic oscillation (NAO) index and series of extended blocking high events [*Scherrer and Appenzeller*, 2006].

[3] This work makes use of almost ten years of new data since the last investigations and additionally considers long-term time series, which have never been analyzed.

2. Data and Methods

[4] The analyses are based on daily, manually measured (from a rod) snow depth data from the observational networks of the Swiss Federal Institute for Snow and Avalanche Research (SLF) and the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). The data were quality checked manually, missing and erroneous values were completed with the help of neighboring stations. For an initial selection 41 stations with more than 60 years of data (at least 1948–2007) could be considered. Seven stations were excluded due to known inhomogeneities or due to the proximity of another, more long-term station nearby. The remaining 34 stations between 200 and 1800 m asl are located throughout Switzerland (Figure S1 of the auxiliary material).[1] Most of these stations experienced one or more changes in their location, observer or environment, which may have biased the time series. The stations were separated into three different altitude zones (201–800 m, 801–1300 m, 1301–1800 m). These zones will be referred to as 'low', 'middle' and 'high' altitude zone. The stations on the southern slope of the Alps were treated separately because their climate is controlled by a distinctly different temperature and precipitation regime (Mediterranean influences) than those north of the Alps.

[5] The number of snow days (SD) between December and March (DJFM) were used in this study, since this value is of more practical use than the mean snow depth. A snow day is defined as a day with a snow depth larger than a given threshold. The thresholds were chosen depending on the practical usability for an activity in the three different altitude zones. Small thresholds saturate at medium altitude (the number of snow days corresponds to the number of days) and larger thresholds are only rarely exceeded at low-lying stations. For these reasons the thresholds of 5, 30 and 50 cm were chosen for the three altitude zones. They correspond to the snow depths required for winter activities typical to each altitude zone, such as building a snowman (5 cm) in the low altitude zone, cross-country skiing (30 cm) in the middle zone and skiing or snowboarding (50 cm) in the high zone. Tests with other appropriate thresholds (0, 10, 20 cm) did not change the results significantly.

[6] In order to investigate trends and possible transitions the non-parametric Mann-Kendall (MK) test in the sequential version [*Sneyers*, 1992] and a regime shift indicator test [*Rodionov*, 2004] were applied to the annual data. The

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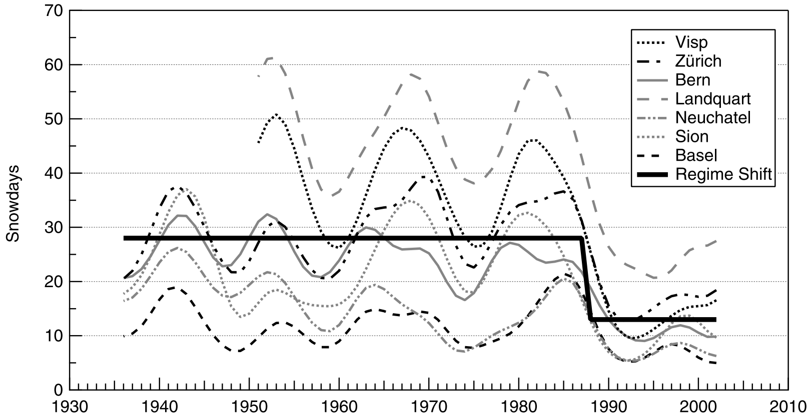

Figure 1. All 7 long-term stations below 800 m asl on the north side of the Alps show a significant step-like decrease in snow days at the end of the 1980's despite large absolute snow days differences due to regional climate influences. The annual values have been smoothed with a 10-year Gaussian low-pass filter. The bold line shows the mean number of snow days (calculated from the annual data) before (1948–1987) and after (1988–2007) the regime shift in 1988.

regime shift indicator test is based on the sequential t-test analysis of regime shifts (STARS). The approach provides flexibility by requiring a user to set a number of parameters: the target significance level, cut-off length, and Huber weight parameter. The target significance level corresponds to the p-level (0.05 in this analysis) of false positives. The cut-off length (30 years in this analysis) is similar to the cut-off length in filtering; it affects the time scale of the regimes by discounting regimes of shorter length. The Huber weight parameter (5 in this analysis) improves the treatment of outliers by weighing them inversely proportional to their distance from the mean value of the regime. By using these parameters, the method utilizes a sequential approach to determine the timing of the regime shifts. The identification of a regime shift is based on calculating the regime shift index (RSI), which represents a cumulative sum of normalized deviations of the time-series values from the hypothetical mean level for the new regime. This is the level for which the difference with the mean level for the previous regime is statistically significant according to Student's *t* test. If the RSI remains positive during a time period equal to the cut-off length, a shift is declared. The size of the RSI is therefore a measure of the magnitude of the shift.

[7] Winters are always named after the main part of the winter (e.g. 2007 refers to winter 2006/2007). To eliminate short-term fluctuations a 10-year Gaussian low-pass filter was often applied to smooth the annual data.

3. Results

3.1. Snow Days North of the Alps

[8] The available stations cover such different regions as the Swiss plateau, the foothills of the Alps or the inner-alpine valleys. The different climates of these regions are responsible for large station-to-station differences of snow days found within the three investigated altitude zones. The 10-year smoothed data of the 7 northern stations in the low altitude zone demonstrate that despite these differences and uncertainties, striking similarities can be found. All stations show fluctuating yet in the long-term stable conditions until about the end of the 1980's and a sharp decline of snow days thereafter. The application of the STARS algorithm on the annual data revealed that all of the stations experienced an abrupt change in snow days since winter 1988 (Figure 1). This step-like change 20 years ago is significant (p-level < 0.05) at all stations. As a consequence, the snow covered period in this altitude zone (mean of all stations) is 2 weeks shorter now than in the 40 years before 1988. This implies that below 800 m asl the probability for days with a snow covered surface has dropped by more than 50%, leaving only 13 snow days per winter (Table 1). A comparison with

Table 1. Year of Shift and RSI of the Step-Like Change Shown by the STARS Test Applied to the Mean of Each Altitude Zone North and South of the Alps With Its Snow Days Threshold[a]

			STARS					
Altitude (m asl)	Th (cm)	Alps N/S	Shift (year)	RSI	SD1 (days)	SD2 (days)	ΔSD (days)	ΔSD (%)
201–800	5	N	1988	0.45	28	13	15 (7)	54
		S	1988	0.16	15	6	9 (3)	60
801–1300	30	N	1989	0.35	55	32	23 (6)	42
		S	1989	0.37	60	40	20 (5)	34
1301–1800	50	N	1988	0.37	93	74	19 (9)	20
		S	1989	0.42	79	54	25 (7)	32

[a] N means north, S means south, Th means threshold, and $p < 0.05$. In addition, the snow days for the 40 years between 1948 and 1987 (SD1), the snow days for the 20 years between 1988 and 2007 (SD2), their difference (ΔSD) with the standard deviation in brackets and the corresponding relative decline (%) are also presented.

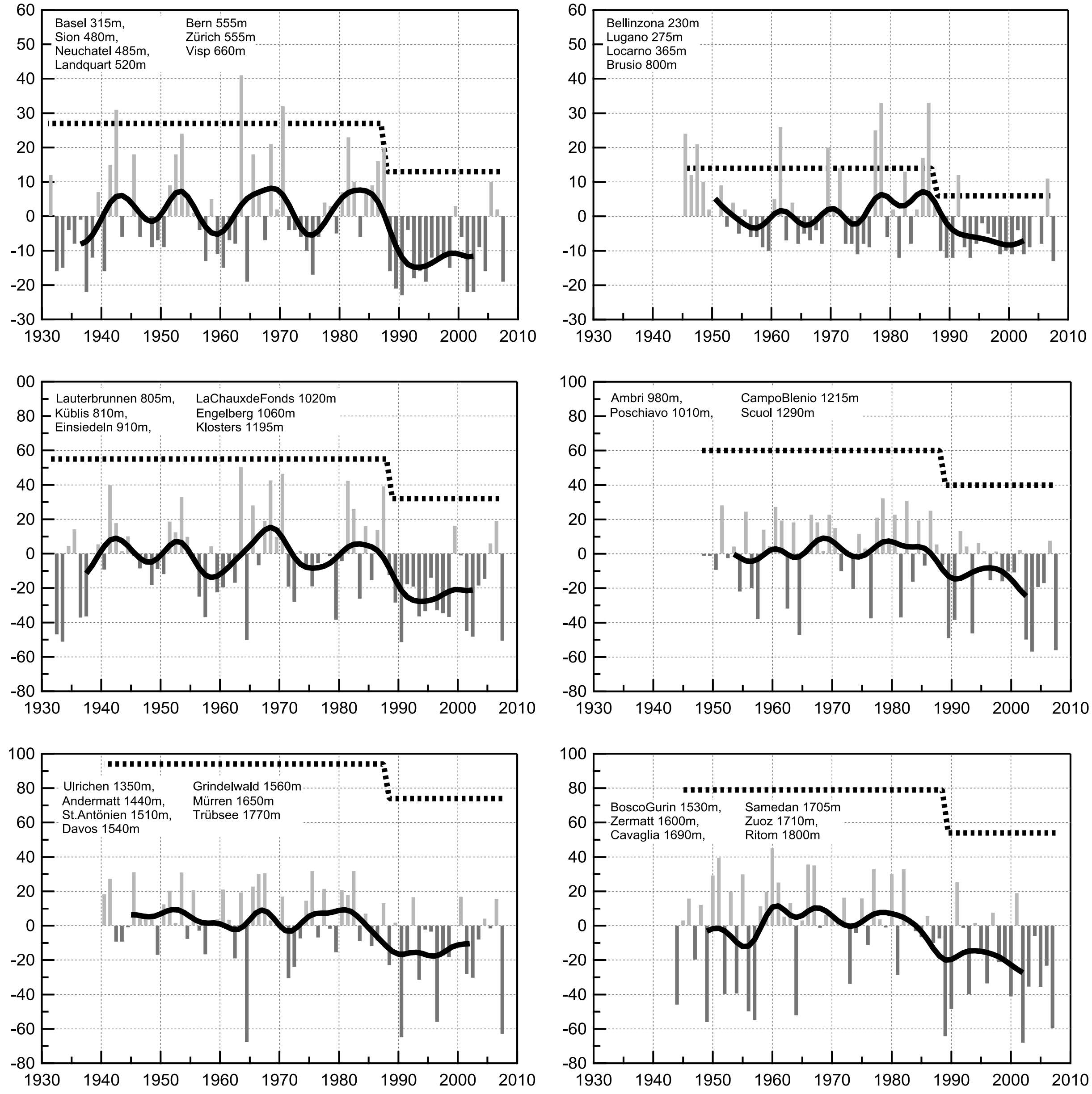

Figure 2. Annual snow days anomalies relative to the current climate norm (1961–1990) for the (top) low, (middle) middle and (bottom) high altitude zones on the (left) northern and (right) southern slope of the Alps. The thick curve represents the 10-year Gaussian low-pass filtered values. The dotted line represents the absolute number of snow days before and after the regime shift found by the STARS algorithm. Note that the scale of the left axis is different for the low altitude zone. The stations used and their altitudes are named in the text box in each graph.

the snow days in Zurich between 1880 and 1960 [*Uttinger*, 1963] indicates that the current situation is unique also when compared to the last 127 years.

[9] All 6 stations of the middle altitude zone show the same pattern with the abrupt change either in 1988 or 1989. The RSI (0.35) of the mean values of all stations is about 20% smaller than in the lower zone, which indicates a slightly less pronounced shift. Nevertheless, the mean reduction in snow days during the last 20 years is more than 3 weeks, which implicates a loss of over 40% (Table 1). In contrast to the lower altitude zone no new low record snow days could be observed since 1988, but the series of low snow winters during the last twenty years is also exceptional (Figure 2). A separate analysis (not shown) of the time series of the station Engelberg, which goes back to 1890, corroborates the uniqueness of the series of snow poor winters during the last 20 years.

[10] The mean of the 7 stations in the high zone also shows an abrupt change in 1988 when the STARS test is applied (Figure 2). The year of the change point is less obvious if the 7 stations are considered individually. One station shows the break only in 1996 and the two highest stations showed no break at all. Nevertheless, the series of low snow days winters during the last 20 years in this altitude zone is also at this altitude zone unique since the beginning of routine measurements in the 1940's. The mean

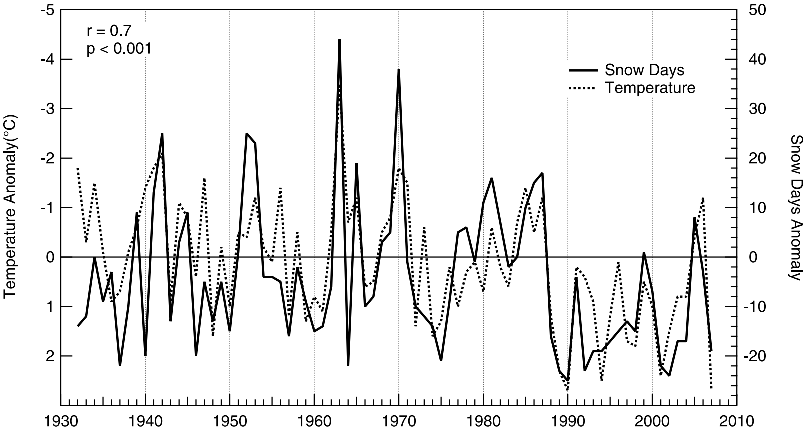

Figure 3. The significant correlation (r = 0.7) between the mean DJFM temperature anomalies (1961–1990) and snow days anomalies below 800 m asl on the north side of the alps demonstrates the influence of the temperature on the evolution of the snow cover. Both curves show the step-like change in the year 1988 towards warmer temperatures and fewer snow days. The left axis is reversed.

decline in snow days of all 7 stations amounts to 19 days, which is 20% of the 93 snow days in the 40 years prior to 1988 (Table 1). The 110-year time series from Davos shows record low snow days at the beginning of the 1930's. This could not be confirmed by the only other station (Samedan) covering the early 1930's in this altitude zone. However, also neither of these two time series shows a multi-year period with such few snow days as the last 20 years.

3.2. Snow Days South of the Alps

[11] There are generally fewer long-term stations on the south side of the Alps and only two stations go further back than the 1940's. The graphs on the right side of Figure 2 represent the snow days on the southern side of the Alps in the same three altitude zones as described above. The results of the STARS test are summarized in Table 1.

[12] The mean of the 4 stations in the low altitude zone shows the same significant drop in 1988, although with a much smaller RSI than north of the Alps. Nevertheless, there were only two winters with positive anomalies in the last 20 years. The drop was therefore caused by the hitherto never observed continuous series of almost snowless winters. The relative decline (58%) is similar to that in the north, but leaves this altitude zone on average with less than a week of snow per winter. The STARS algorithm individually applied to the 4 stations revealed no break at all for one station.

[13] The mean of the 4 stations in the middle altitude zone shows the abrupt change in 1989 with new record lows during the last five years. This accounts for a reduction in snow days of almost 3 weeks (34%) in the last twenty years, which roughly corresponds to the decline observed on the other side of the Alps. The STARS algorithm individually applied to the 4 stations revealed the break for one station only in 2002. The absolute amount of snow days is slightly higher than on the north side due to the fact that only one of the 4 stations in this zone is below 1000 m asl. This is in contrast to the two other altitude zones, which show fewer snow days on the south side due to generally warmer temperatures. Looking at individual winters it is striking that 4 of the 5 winters with the least snow days were all observed in the last 20 years.

[14] The situation in the high zone is again similar to that on the north side. The STARS test reveals an abrupt change in 1989 for the mean of all 6 stations, but the individual stations show the step for one station already in 1983 and for two others in 1993 and 1996. The observed mean reduction of snow days is 25 days (32%), which is in absolute terms the largest reduction of all zones.

3.3. Trend Analysis of the Last 20 Years

[15] When looking only at the last twenty years in the anomaly graphs of the three altitude zones (Figure 2) it seems that there is no clear trend since the step-like decrease at the end of the 1980's. The MK-test confirms this observation. None of the test results of the mean values of none of the three altitude zones on both sides of the Alps show a significant increasing or decreasing trend. A simple linear regression analysis reveals insignificant decreasing trends for the mid and high altitude zones on the southern side of the Alps. This downward trend of snow days may also be caused by the simultaneous decrease in snow precipitation on the south side of the Alps [*Valt et al.*, 2005]. The forthcoming years will show whether this trend will continue or not.

3.4. Possible Cause of the Regime Shift

[16] The number of snow days for the low altitude zone show a significant correlation (r = 0.69) with the Swiss DJFM winter temperatures [*Begert et al.*, 2005], including the abrupt change in 1988 (Figure 3). The sensitivity to temperature is not surprising since Swiss winter temperatures below 1800 m asl are often close to the melting point. The mean freezing level of the last 50 winters is at 860 m asl. [*Frei et al.*, 2007], which is (not coincidentally) close to the altitude of the maximum snow sensitivity (740 m) [*Wielke et al.*, 2004]. Moreover, *Scherrer et al.* [2004] demonstrated that temperature and not precipitation is the driving factor for the change of snow days in Switzerland. Knowing that winter temperatures in the last twenty years were highest since the beginning of measurements in 1864 [*Begert et al.*, 2005] and probably even since 1500 [*Luterbacher et al.*, 2007] indicates that Switzerland experienced the least snowy winters since a long time in

the last twenty years. The fact that the European winter temperature [*Brohan et al.*, 2006] (between 15W–40E and 35–70N) reveals exactly the same step-like change in 1988 and is also significantly correlated (r = 0.55) with the number of snow days indicates that the phenomena is not focused on the Alps and has its origin on a larger scale.

[17] The shift-like increase of temperature at the end of the 1980's and the simultaneous step-like decrease in snow days may be explained by the influence of large scale flow patterns (blocking highs events and strongly positive NAO indices) [*Scherrer and Appenzeller*, 2006] and the concurrent transition from solar dimming to solar brightening climate [*Norris and Wild*, 2007]. The influence of the blocking high events is supported by the fact the DJFM pressure data of Zürich and Säntis (1931–2007) also shows a regime shift in 1989 (with an increase of 3 hPA in the last 20 years). The pressure data and the NAO index returned to more normal values in the last 13 years, which might be an explanation for the slight rebound of snow days after 1995. This would imply that the full rebound is not possible due to higher winter temperatures caused by the full magnitude of the greenhouse effect, which is no longer masked by solar dimming.

4. Summary and Conclusions

[18] This study demonstrates that, when considering medium to long-term averages, there is a close resemblance between the snow cover at stations at similar altitudes, despite heterogeneity between individual sites and possible station inhomogeneities. The long-term data of several stations of similar altitude will thus give a spatially reliable picture of a specific elevation zone. This emphasizes the need to continue snow observations at different altitude zones on both sides of the Alps in order to monitor further possible changes.

[19] The analysis of the snow cover in terms of snow days revealed that Swiss winters are more strongly characterized by a remarkable and significant step-like change in snow days at the end of the 1980's than by a long-term downward trend. In fact, an analysis with MK-test demonstrates that the step-like decline is responsible for the decreasing trend of a series. For 3 of the 6 cases the trend is significant ($p < 0.05$) but only if the last 7 years are included. There is not a great deal of confidence in the stability of such a trend, since it is at the very end of the over 60-year data series. Regarding the timing of the stepwise change the low altitude zone revealed the most homogenous pattern among the stations and most dramatic reduction in snow days (over 50%). The higher stations (especially on the south side) show a more diverse picture, but the mean of the stations revealed also for these zones the step-like change at the end of the 1980's.

[20] When only the 20 years after the regime change are considered no clear trend can be detected. The average of the last twenty winters shows record low snow days for both sides of the Alps since the beginning of measurements more than 100 years ago. The fact that the abrupt change could not only be detected at the city stations, but also at rural and mountain stations demonstrates that something like the urban heat island effect can not be responsible for the sharp decline in snow days after end of the 1980's.

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