

Seasonal trends and temperature dependence of the snowfall/precipitation-day ratio in Switzerland

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[1] This paper analyzes the proportion of snowfall days relative to precipitation days, in order to assess the impact of changing temperatures on snowfall, while minimizing the impact of variations in precipitation frequency and intensity. We analyzed the ratio of snowfall days to precipitation days for up to 100 years at 76 meteorological stations, spanning elevations from 200 to 2700 m asl in Switzerland. Our results show clear decreasing trends in snowfall days relative to precipitation days. These decreases are connected to increasing temperatures. The decrease in snowfall days was stronger at lower elevations, i.e., at locations with temperatures closer to the melting point. We observed a baseline seasonal temperature threshold of $-2.7^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$ in winter and $-3.8^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$ in spring, above which the decrease in snowfall days grew rapidly. From these observations, we developed an empirical model that can be used to evaluate the impact of future temperature increases on snowfall, independent of changes in the frequency and intensity of precipitation events. **Citation:** Serquet, G., C. Marty, J.-P. Dulex, and M. Rebetez (2011), Seasonal trends and temperature dependence of the snowfall/precipitation-day ratio in Switzerland, *Geophys. Res. Lett.*, 38, L07703, doi:10.1029/2011GL046976.

1. Introduction

[2] A general decreasing trend in snow cover has been clearly demonstrated in the Northern Hemisphere [Intergovernmental Panel on Climate Change (IPCC), 2007]. It has also been shown for mountain regions [e.g. Ke et al., 2009; Micu, 2009; Morin et al., 2008; Xu et al., 2008], in particular for the European Alps [Hantel and Hirtl-Wielke, 2007; Schoner et al., 2009; Wielke et al., 2004], including the Swiss Alps [Laternser and Schneebeli, 2003; Marty, 2008; Scherrer et al., 2004; Scherrer and Appenzeller, 2006; Wielke et al., 2004]. Decreasing trends in the proportion of snow water equivalent to total or extreme precipitation have also been investigated at several locations in the United States and Japan [Feng and Hu, 2007; Huntington et al., 2004; Knowles et al., 2006; Takeuchi et al., 2008]. The decrease in snow cover is statistically significant in many locations at least since the early 1980s or late 1970s [Hantel and Hirtl-Wielke, 2007; IPCC, 2007; Laternser and Schneebeli, 2003]. However, particularly in the European Alps, the high interannual variability in precipitation amounts and the impact of the NAO index have created uncertainty [Durand et al., 2009; Marty, 2008;

Morin et al., 2008; Scherrer et al., 2004; Scherrer and Appenzeller, 2006; Schoner et al., 2009]. The exact impact of changing temperatures is difficult to measure because of the potentially large variation in total precipitation through time. In addition, the impact of increasing temperatures varies, depending on region and altitude [Scherrer et al., 2004; Scherrer and Appenzeller, 2006; Wielke et al., 2004; Xu et al., 2008].

[3] In this paper we seek to isolate the impact of changing temperatures on snowfall from the impact of changes in the frequency and intensity of total precipitation. Our approach is to analyze the proportion of snowfall days compared to precipitation days. This simple measure does not require high-quality snow water equivalent data or estimates of the phase change based on temperature. This day-based snow/precipitation ratio is complementary to other methods that compare the snow water equivalent to total precipitation volume [Feng and Hu, 2007; Jonas et al., 2009; Knowles et al., 2006; Laternser and Schneebeli, 2003]. We determine the relative frequency of snowfall, independent of the variability in timing and intensity of precipitation events, in order to isolate the impact of long-term temperature trends on snowfall.

[4] Our method aims to characterize more precisely the impact of increasing temperatures on snowfall frequency stratified by season and elevation. We chose Switzerland for this analysis to take advantage of its particularly dense network of snow and precipitation stations: in just 41,000 sq km of terrain, there are 76 stations with at least 30 years of daily data. This dense observational network has been used to investigate the consequences of climate change in general, and particularly to study the decrease in snow cover through time [Laternser and Schneebeli, 2003; Marty, 2008; Scherrer et al., 2004; Scherrer and Appenzeller, 2006; Wielke et al., 2004]. Here we compute the seasonal trend in the proportion of snowfall days relative to precipitation days during the last 30 to 100 years at elevations up to 2,700 m asl.

2. Data and Methods

[5] We used daily precipitation and snowfall measurements, as well as monthly average temperature data, from 76 Swiss meteorological stations located between 200 m asl and 2700 m asl. Snowfall was manually measured by the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) and the WSL Institute of Snow and Avalanche Research SLF, and compared to nearby precipitation and temperature data collected by MeteoSwiss. We excluded all series that ended before 2005 or that were shorter than 30 years. We also excluded series with more than 10% data missing during the two time intervals that we analyzed (1961–2008 and 1979–2008). 1961 and 1979 correspond to

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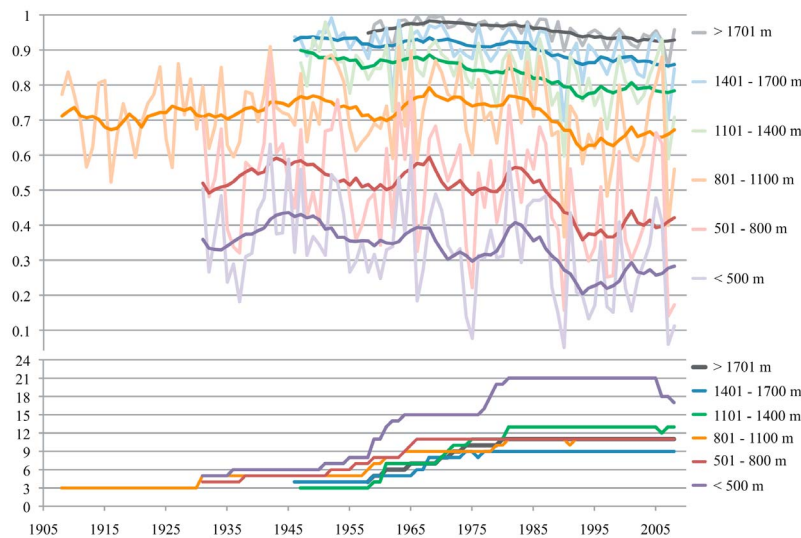


Figure 1. Winter (December–January–February) mean ratio of snowfall versus precipitation days (SD/PD) by altitudinal categories from 1908 to 2008. Bold lines are unweighted moving averages with an 11-year window (with uncorrected 5-year edges using the available points). The lower panel shows changes in the number of available stations through time.

two thresholds when new series of data became available: 52 and 76 stations respectively (Figure 1). We computed the monthly sum of precipitation days (PD) and the monthly sum of snowfall days (SD). Following common practice, we chose a threshold of 1 mm of total precipitation to define a PD and 1 cm of snow to define a SD. We considered all days with at least one cm of snow (that is, all SD's) as also being PD's, even in cases where the total precipitation was missing or recorded as less than 1 mm. Thus SD's are a subset of PD's. To examine the evolution of the SD/PD ratio through time (Figure 1), we grouped the stations into six altitude classes (< 500 m asl, 501–800 m asl, 801–1100 m asl, 1101–1400 m asl, 1401–1700, and > 1701 m asl). In Figure 1, we show the average SD/PD ratio, calculated whenever there were at least three stations per altitude group. We computed the SD/PD ratio of every meteorological station for winter (December–January–February) and for spring (March–April). For spring, we eliminated the stations below 900 m asl because they have too few SD's. For each station and each season, we calculated the long-term linear regression trends in the SD/PD over the two analysis periods (1961–2008 and 1979–2008). We then compared the fitted regression values for the beginning and end of each period (1961 and 2008, or 1979 and 2008), to estimate the percentage changes in SD/PD over the two intervals (48 and 30 years, respectively). We correlated the changes in winter and spring SD/PD at each meteorological station with the station's altitude in m asl. We also correlated the SD/PD changes at each station with the seasonal temperature (i.e., winter or spring, as defined above), averaged over a decade surrounding the beginning of each analysis interval (i.e., 1956 to 1965, and 1974 to 1983). We characterized the seasonal baseline temperature for each station using these decadal averages rather than the individual years 1961 and 1979, in order to minimize the effects of interannual variability in the temperature data. Due to limitations in the available temperature records, these seasonal baseline temperatures could

only be defined for a subset of the stations (46 for 1961–2008 and 64 for 1979–2008).

3. Results

[6] Our data, starting in 1908 for three stations between 800 and 1100 m asl and later at the other elevations, show a general decreasing trend in SD/PD, particularly during the 1980s and 1990s (Figure 1). The winter SD/PD's decreased over the intervals 1961–2008 and 1979–2008 for all stations at all elevations, with 60% of the trends being statistically significant ($p < 0.05$) for 1961–2008 and 29% for 1979–2008. The spring SD/PD's decreased at 89% of the stations over the interval 1961–2008, and at 98% of the stations over the interval 1979–2008. 46% of the spring trends were significant ($p < 0.05$) for 1961–2008 and 50% for 1979–2008.

[7] The correlations between station altitude and SD/PD changes were significant ($p < 0.01$) or highly significant ($p < 0.001$), both for winter and for spring (Figure 2). For the two time periods, our results show that the decrease in SD/PD was greater at lower altitude than at higher altitude, and also greater in spring than in winter (Figure 2 and Table 1). The correlations between SD/PD changes and the stations' baseline temperatures were also significant ($p < 0.01$) or highly significant ($p < 0.001$), both in winter and in spring (Figure 2). For the two time periods and for almost all baseline temperature values, the decrease in SD/PD was greater in spring than in winter. The higher the baseline temperature, the stronger the decrease was in the SD/PD ratio (Table 1). For stations with relatively low baseline temperatures, the changes in SD/PD mostly ranged from +10 to –20%, whereas for stations with higher baseline temperatures, the decreases ranged as high as 80% over the period 1979–2008. Results of the quadratic equations show that stations whose SD/PD ratios decreased more than 20% had baseline temperatures at the start of the period that lay above a threshold of $-2.7^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$ in winter and $-3.8^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$ in spring.

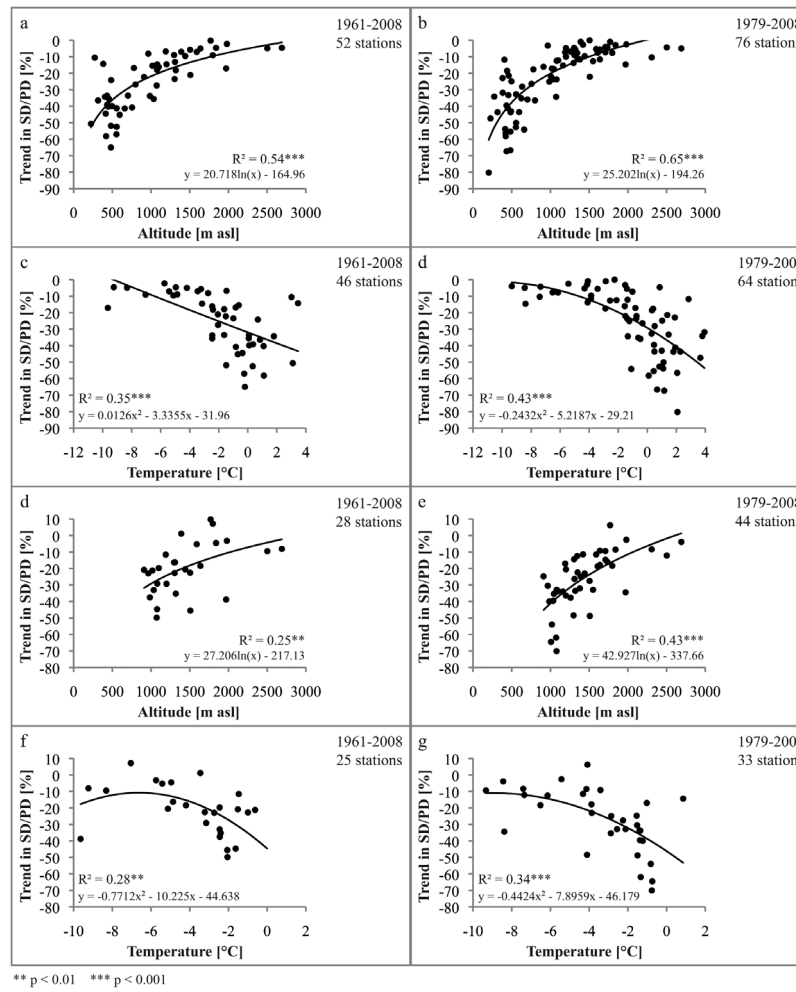


Figure 2. Changes in (a–d) wintertime SD/PD and (e–h) springtime SD/PD during the two study periods [%] as a function of altitude [m asl] (Figures 2a, 2b, 2e and 2f) and baseline seasonal temperature at the start of each study period (Figures 2c, 2d, 2g and 2h).

Table 1. Changes in SD/PD [%] for Selected Station Altitudes, for Selected Baseline Temperatures [°C] and Changes in SD/PD [%] Expected per 1 K Temperature Increase for Selected Baseline Temperatures [°C] for the Winter and Spring Seasons During the Intervals 1961–2008 and 1979–2008

Time Periods	Changes in SD/PD [%] for Selected Station Altitudes [m asl]			Changes in SD/PD [%] for Selected Baseline Temperatures [°C]			Changes in SD/PD [%] Expected per 1 K Temperature Increase		
	Altitude [masl]	Winter	Spring	Temp [°C]	Winter	Spring	Temp [°C]	Winter	Spring
1961–2008	500	−36.2	−48.1	−8	−4.5	−12.2	−8	−2.4	−6.6
	800	−26.5	−35.3	−6	−11.5	−11.1	−6	−6.2	−5.9
	1100	−19.9	−26.6	−4	−18.4	−16.1	−4	−9.9	−8.6
	1400	−14.9	−20.0	−2	−25.2	−27.3	−2	−13.6	−14.7
	1700	−10.9	−14.8	0	−32.0	−44.6	0	−17.2	−24.0
	2000	−7.5	−10.3	2	−38.6	−68.2	2	−20.7	−36.7
	2300	−4.6	−6.5	4	−45.1	−97.9	4	−24.2	−52.6
1979–2008	500	−37.6	−70.9	−8	−3.0	−11.3	−8	−2.3	−8.8
	800	−25.8	−50.7	−6	−6.7	−14.7	−6	−5.1	−11.4
	1100	−17.8	−37.0	−4	−12.2	−21.7	−4	−9.4	−16.7
	1400	−11.7	−26.7	−2	−19.7	−32.2	−2	−15.3	−24.9
	1700	−6.8	−18.4	0	−29.2	−46.2	0	−22.6	−35.7
	2000	−2.7	−11.4	2	−40.6	−63.7	2	−31.4	−49.3
	2300	0.8	−5.4	4	−54.0	−84.8	4	−41.7	−65.6

[8] During the two observation periods, the mean annual temperature in Switzerland (calculated from the 12 Meteo-Swiss reference stations with homogenized temperature records [Begert *et al.*, 2005; Rebetz and Reinhard, 2008]) has increased by 1.82 K (1961–2008) and 1.48 K (1979–2008), while mean winter temperature has increased by 1.86 K and 1.29 K, respectively, and mean spring temperature has increased by 1.96 K for both periods.

[9] We created a simple empirical model for the SD/PD changes in our study region, using the regression curves shown in Figure 2. We calculated the SD/PD changes predicted by these regression curves for selected altitudes (Table 1) and baseline temperatures (Table 1). We then normalized these predicted changes for baseline temperatures by the observed national average winter temperature changes over the two study periods (1.86 K and 1.29 K, respectively), to obtain the corresponding decrease in SD/PD ratio per 1 K, as a function of the starting baseline temperature. These normalized SD/PD changes allow us to estimate the impact of a future temperature rise on the SD/PD ratio in this region.

4. Discussion

[10] There was a general decrease in SD/PD, both for winter and spring. This decrease was clearly more pronounced at lower than at higher elevation. This is because the temperature is more frequently close to the melting point at lower elevations. It will be even more so in a warmer climate. SD/PD's would be expected to decrease much less at higher altitudes, where temperatures are generally much lower than the melting point. A general increase in temperature, even by 1.48 or 1.82 K, as observed in the region since the 1960s or 1970s, still leaves higher locations with a temperature generally much lower than the melting point and thus with little or no impact on the snowfall part of precipitation.

[11] The higher decrease in SD/PD observed in spring compared to winter can be attributed in part to higher temperatures, i.e., temperatures more frequently close to the melting point. The higher decrease in SD/PD in springtime may also be attributed to the higher temperature increase observed in spring, compared to winter, during both periods (1961–2008 and from 1979–2008). Our results show that the impact of increasing temperatures was clearly higher for baseline temperatures above a threshold of $-2.7^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$ in winter and $-3.8^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$ in spring. These baseline temperature thresholds can be considered as the turning point for decreases in the SD/PD ratio. These thresholds can be compared with the -5°C threshold observed by Knowles *et al.* [2006] for wet-day minimum temperature between November and March in the Western United States. The abrupt change in SD/PD at the end of the 1980's for stations below 1100 m asl demonstrates that the decreasing snow cover in the Alps as observed by Marty [2008] and Durand *et al.* [2009] is at least partly due to a phase change in the precipitation regime.

[12] Our results allow future snowfall decreases to be estimated from predicted temperature increases and current baseline seasonal temperatures (Table 1). For instance, for a future temperature rise of 1 K, in locations with a present winter temperature of -8°C , our empirical model shows a decrease in SD/PD of 2.3 to 2.4%, whereas for a present

temperature of -1°C , we can expect a decrease of 15.4 to 18.7% (Table 1). We consider that these estimates should be most applicable to temperature increases between 1.5 and 2 K, corresponding to the observed increase during our study periods.

5. Conclusions

[13] Our analysis of trends in snowfall days (SD) relative to precipitation days (PD) over 76 stations between 200 and 2700 m asl in Switzerland shows clear decreasing trends in connection with increasing temperatures during the study periods (1961 to 2008 and 1979 to 2008). SD/PD's decreased both in winter (DJF) and in spring (MA), with even stronger decreases during spring, probably because baseline temperatures were warmer, and temperature increases were greater, during that season. The decrease in SD/PD was clearly greater at lower elevations, i.e., at locations with temperatures closer to the melting point, with a threshold corresponding to baseline temperatures of $-2.7^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$ in winter and $-3.8^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$ in spring. Above these thresholds, the decrease in SD/PD ratios could be as high as 80% over the 30 years from 1979 to 2008. Our results form the basis of an empirical model that can be used to evaluate the impact of future temperature increases on snowfall. This model should be most reliable for temperature increases between 1.5 and 2 K. Depending on the present seasonal temperature at one location, we can compute the impact of temperature increases on the incidence of snowfall days, independent of the frequency and intensity of the precipitation events.

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