Trends in Swiss Alpine snow days: The role of local- and large-scale climate variability

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[1] Swiss Alpine snow cover is varying substantially on interannual to decadal time scales. In the late 20th century decreases in snow days (SD) have been observed for stations below 1300 m asl. A regression model is used in this work to quantify the importance of mean temperature and precipitation as well as large-scale climate variability in order to explain the observed trends. Both, local- and large-scale models account for a modest fraction of the observed seasonal variability. Results suggest that the recent decrease in low altitude snow cover can mainly be attributed to an increase in temperature. Differences are found for northern and southern Switzerland concerning the influence of large-scale climate patterns. In contrast to southern Alpine regions, northern Alpine interannual SD variability is almost unaffected by the North Atlantic Oscillation (NAO). Decadal trends, however, can be explained via temperature only by a model that includes the explanatory variable NAO. **INDEX TERMS:** 1630 Global Change: Impact phenomena; 1620 Global Change: Climate dynamics (3309); 1863 Hydrology: Snow and ice (1827). **Citation:** Scherrer, S. C., C. Appenzeller, and M. Laternser (2004), Trends in Swiss Alpine snow days: The role of local- and large-scale climate variability, *Geophys. Res. Lett.*, 31, L13215, doi:10.1029/2004GL020255.

1. Introduction

[2] Snow is a resource of great commercial and social value for the Swiss Alpine region (tourism, drinking water reservoir, hydro-electricity) but it also bears considerable hazards (avalanches, road closures) [e.g., Beniston *et al.*, 2003; Elsasser and Messerli, 2001]. However, the number of snow days (SD) varies substantially on interannual to decadal time scales. A decrease has been reported for low altitude stations in the late 1980s and 1990s [Laternser and Schneebeli, 2003]. A similar decline in spring snow cover has been found for other mountain regions of the world [Brown, 2000; Mote, 2003]. For most stations the decline coincided with a significant increase in local temperature.

[3] Several studies point out a pronounced impact of seasonal climate modes on snowpack in the Western USA [Cayan, 1996; McCabe and Dettinger, 2002]. In the European region the North Atlantic Oscillation (NAO) is the leading climate mode of seasonal to decadal variability

[Hurrell, 1995]. However, since Switzerland is located between the poles of the NAO temperature impact, the NAO influence in the Alpine region is ambiguous. Large-scale upper air fields such as pressure and stratospheric ozone are rather strongly forced by the NAO variability [Appenzeller *et al.*, 2000; Beniston, 1997]. Surface and possibly smaller scale variables such as precipitation seem to be dominated by other modes on the seasonal to interannual time scale [Massacand and Davies, 2001; Schmidli *et al.*, 2002].

[4] This work examines the influence of local seasonal mean temperature and precipitation as well as seasonal large-scale Euro-Atlantic climate patterns of sea level pressure (SLP) on Swiss Alpine midwinter snow day variability and trends.

2. Data and Methods

2.1. Snow and Climate Data

[5] DJF SD have been calculated from a quality checked snow dataset covering the Swiss Alps and parts of the forelands described in detail by Laternser and Schneebeli [2003]. A subset consisting of 110 almost complete and spatially almost uniformly distributed daily snow height measurements ranging from 275 m to 2540 m asl and covering the period from 1958 to 1999 was used in this study. SD were defined as days with a snow height of more than 5 cm as suggested by Hantel *et al.* [2000]. Local seasonal temperature and precipitation time series at the snow stations were derived from 67(360) carefully homogenized monthly temperature (precipitation) observations [Begert *et al.*, 2003]. The interpolation to the snow station coordinates was achieved by linear fits to the station height using the 5(10) nearest surrounding temperature (precipitation) stations as predictors. The DJF mean SLP fields were derived from the European reanalysis project (ERA 40) data set.

[6] The region of interest is cut by the Alpine mountain divide into the southern part of Switzerland which is partially affected by the Mediterranean regime and the northern part which is more directly influenced by the Atlantic mid-latitude westerlies.

2.2. Statistical Methods

[7] Interannual to decadal scale trends were analyzed using ordinary least square 15-yr running window trends. Standard principal component analysis was used to determine the leading SLP patterns [Wilks, 1995]. The first principal component of the DJF SLP fields over the Euro-Atlantic region [80°W–60°E, 30°N–80°N] turned out to be

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Figure 1. Variability and saturation of DJF Swiss snow days with respect to altitude (units: m). The green triangles show a robust estimation of the standard deviation expressed as the inter quartile range divided by 1.349 (upper horizontal axis, units: days). The median percentage of DJF days classified as snow days is depicted by black dots (lower horizontal axis). The thick lines are lowess ($f = 0.3$) smoothed curves to the corresponding data.

virtually identical with a station based NAO index as defined by Hurrell [1995].

[8] Standard linear regression analysis was used to quantify how well seasonal SD sums can be modeled (i) by taking local seasonal mean temperature (T) and mean precipitation (P) as explanatory variables and (ii) by taking large-scale climate patterns represented by the first 6 SLP principal components (PC's) as explanatory variables [cf. Junge and Stephenson, 2003]. For the latter the local snow day anomaly ΔSD^k is thus modeled as

$$\Delta SD^k = \sum_{i=1}^6 \alpha_i^k \cdot SLP_{PCi} + \varepsilon \quad (1)$$

where α_i^k are the coefficients to be fitted, ε is an independent identically distributed error and k is the index of the stations considered. Optimal model sets were selected using a stepwise forward and backward selection procedure. Absolute model trends that can be attributed to T and P were determined following the method described by Mote [2003].

3. Results

3.1. Snow Day Variability and Trends

[9] The number of SD is difficult to analyze in a statistical sense. Its variability in mean and standard deviation is large and highly dependent on altitude. In mid-winter (DJF), SD saturation occurs for stations with heights above ~ 1300 m asl, indicating snow cover over the entire season (Figure 1). This inhomogeneity of the variability with altitude and our focus on low altitudes makes it reasonable to restrict the interpretation of the model results to altitudes below this saturation level.

[10] The trends in Swiss SD are displayed in Figure 2 as time-height sections using a 15-yr running window trends. No uniform trend is discernible over the whole period. Negative trends are observed at the beginning and at the end, positive trends in between. The most striking decline is found at the end of the observation period. Relative

trends are large for low and negligible for high stations (Figure 2 (top)). This low-high altitude dissimilarity is a direct consequence of the declining variability and the saturation with altitude (cf. Figure 1). The station height of maximum trends (~ 600 m) is of the same order as the current height of maximum sensitivity in Switzerland and Austria [Hantel *et al.*, 2000]. Absolute trends are less dependent on altitude, but the largest trends are again found for relatively low stations (Figure 2 (bottom)).

[11] Although SD reveal considerable interannual to decadal variability, it is common to compute linear trends for the whole 42 yr time period considered. The corresponding relative observed trends are shown in Figure 3. The results are consistent with the decadal trend plots discussed above. Relative trends are negligible for stations above ~ 1300 m, whereas large negative trends are found for lower stations. Both northern and southern Swiss SD trends are similar with slightly smaller trends in the southern regions.

[12] The strong altitudinal dependence of trends is in general a typical sign of a T shift since relative changes in SD (similar as for snow water equivalent) are quite uniform with altitude for changes in P [Mote, 2003]. A moderate shift in T on the other hand can change the fraction of P that falls as snow considerably. To test the above statement, local T and P models are constructed in the next section.

3.2. Local Temperature and Precipitation Models

[13] Earlier studies on climatological snow variability showed that to a first approximation local T and P have a large impact on local snow water equivalent [Mote, 2003].

Figure 2. Time-height section of decadal Swiss snow day trends. Upper panel: relative 15-yr running window trends (units: %/yr), lower panel: absolute 15-yr running window trends (units: days/yr). Blue (red) circles show positive (negative) trends. Significant trends according to a two sided t-test on the 10% level are filled and have a black border. The height distribution of the snow stations is indicated by dashes on the right side. A scale for the circles is shown in both panels.

Figure 3. 1958–1999 observed and modeled linear snow day trends. Shown are relative trends (units: %/yr) for the observations (green circles), combined temperature and precipitation (red triangles) and precipitation only model (blue squares). Results for northern (NCH) and southern Switzerland (SCH) are shown in the left (right) panel.

Table 1 indicates that Swiss Alpine midwinter SD variability can be described with modest success using a statistical model that comprises seasonal local mean T and mean P as explanatory variables. For stations below 1000 m asl the explained variance is $\sim 45\%$ (35%) for northern (southern) Switzerland. The T_{only} model results suggest that most of the explained variability is explained by mean T variability. This is no surprise since DJF mean T for these low regions are around 0°C , where already small variations determine whether P falls as snow or rain. The influence of P is stronger for southern than for northern Switzerland, indicating that SD on the southern side of the Alps might also be P limited (cf. Table 1). The relatively moderate percentage of overall variability explained suggests that either temporal variability and/or other (local) effects in the sub-seasonal range which are lost by seasonally averaging play an important role.

[14] The observed long-term trends can be modeled rather well using the above model (Figure 3). The combined T and P model explains more than 50% of the trend observed for northern Switzerland. The P_{only} model on the other hand is not able to reproduce any reasonable trends. This is a further indication, that the recent negative Swiss Alpine snow day trend is mainly T determined. It is consistent with the hypothesis discussed in the previous section and the results found for the Pacific Northwest region of the USA [Mote, 2003].

[15] The absolute model trends that can be attributed to T and P are quantified in Figure 4. Although the fit considerably underestimates the trends for certain stations in analogy to the results found by Mote [2003], it reveals that the increasing trends in mean T explain almost all of the modeled decreasing snow day trends. The mean T contri-

bution is particularly large for stations below 1000 m asl independent of region. The P related trends are in general very small (e.g. Figure 4 (left)). A weak P related increase in SD is found for stations north of the Alpine mountain divide, whereas a weak P related decrease appears on the southern regions (Figure 4 (right)).

3.3. Large-scale Influences on Variability and Trends

[16] The variability in local variables discussed above is mainly related to larger-scale atmospheric flow variations [Beniston, 1997]. For North America it was shown, that the influence of synoptic scale flow patterns as well as seasonal climate modes on local snow water equivalent is crucial [Cayan, 1996; Dettinger and Cayan, 1995; McCabe and Dettinger, 2002]. Furthermore, large-scale climate modes such as the NAO are important in quantifying recent global change impacts [see, e.g., Hurrell et al., 2003].

[17] The snow day multiple R^2 of models with seasonal large-scale climate patterns (SLP PC's) as the only explanatory variables are similar to models that use local seasonal mean T and P (Table 1). Higher values (up to 70%) are again found for low stations. These numbers reflect that large-scale SLP patterns as a single variable are a fairly good predictor of low station SD variability. They also suggest that the large-scale impact on local variables is not necessarily smaller for low than for high altitudes. The major reason is the vulnerability of snow on the 0°C temperature threshold. Temperatures at higher stations are more often below 0°C and therefore fallen snow persists without direct reaction on T variations.

[18] By including and excluding the first PC of the seasonal SLP pattern into the model, the role of the NAO in explaining the observed Swiss SD variability can be quantified. For northern Switzerland the model without NAO has a multiple R^2 only marginally smaller than that of the full model (Table 1). For southern Switzerland the model without NAO loses more than half of the full model value R^2 . Hence, the NAO alone plays a minor role in

Figure 4. Snow day trends attributed to local mean temperature and precipitation based on the local snow day model (units: days/42yrs). (left) precipitation (x-direction) vs. temperature (y-direction) attributions. The grayscale of the points shows station altitude: the higher the station, the darker the points. Contour lines depict total (temperature plus precipitation) trends (units: days/42yrs). (right) Latitude (S-N) vs. altitude section. The trends attributed to precipitation (x-direction) and temperature (y-direction) are shown as pseudo vectors. Similar to the left panel the 135° line divides positive and negative combined trends (see inset in the upper left corner).

Table 1. Mean multiple R^2 for different kinds of linear snow day models applied to northern (NCH) and southern Switzerland (SCH) stations below 1000 m asl

Model Type	Predictors	Multiple R^2 (%)	
		NCH	SCH
Local	P_{only}	8	14
	T_{only}	35	23
	T and P	45	35
Large scale	$PC1(\text{NAO})$	6	20
	$PC2-6$	37	12
	$PC1-6$	43	32

Figure 5. As Figure 3, but for large-scale climate pattern model trends. Shown are the results for the full (SLP PC1-6) model (red triangles) and the non NAO (SLP PC2-6) model (blue squares).

determining the interannual SD variability in northern Switzerland ($0 < R^2 < 20\%$, dependent on station height), whereas for southern Switzerland the NAO is the most important model component. This is in agreement with studies that found a pronounced NAO impact on precipitation in the regions influenced by Mediterranean climate [Quadrelli *et al.*, 2001].

[19] The NAO influence is enhanced substantially when longer term trends rather than interannual variability are investigated. The relative linear trends with respect to altitude are depicted in Figure 5 for the optimal full SLP PC as well as the optimal SLP model without NAO. The latter underestimates the trends considerably for northern Switzerland and fails completely to explain any trend for southern Swiss stations. The models including the NAO are able to model most of the observed trend, although there is still an underestimation for northern Switzerland.

[20] To strengthen the hypothesis that the NAO variability can mainly explain decadal scale trends, the models were rerun and optimized for low and high pass filtered predictands and predictor fields. The low pass filter applied to the yearly time series was a five point triangular filter. High pass filtered values were constructed by subtracting the original from the low pass filtered data. For southern Switzerland, 88% of the stations include the NAO in both (low and high pass) optimal models. This suggests that the NAO not just explains trends but also considerable parts of interannual SD variability. Different results are found for the northern side of the Alpine mountain divide. A relatively small number of stations (35%) include the NAO as explanatory variable in the high pass filtered SD data. This again suggests that interannual SD variability is not primarily linked to NAO variability. The increase to 57% for the low pass filtered data corroborates the presumption that the NAO is important on decadal time scales.

4. Conclusions

[21] In the late 20th century, Swiss midwinter Alpine snow cover showed a pronounced decrease at low altitude stations. Our statistical model results indicate that this decrease can mainly be attributed to an increase in seasonal mean temperature. Seasonal mean precipitation neither explains large amounts of variability nor affects recent trends in a substantial manner. Differences are found for the northern and southern parts of Switzerland concerning the influence of the NAO in explaining snow day variability. NAO related year-to-year

variability is of minor importance for northern Switzerland but relevant for southern Switzerland. NAO related decadal variability was necessary for an adequate statistical description of decadal scale SD trends on both sides of the Alps but again with stronger impact on the southern side.

[22] Finally, note that the late 20th century NAO trends might simply be natural decadal variability. However, if there is indeed a global change related trend to more frequent positive NAO index winters in the 21st century, as seen in some climate change model scenarios [e.g., Hurrell *et al.*, 2003], our results indicate a stronger decrease in low altitude snow cover than expected from a global mean temperature increase alone.

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