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Article

Snow cover duration in Switzerland compared to Austria

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Abstract

The sensitivity of the number of days with snow cover at Swiss climate stations relative to the mean temperature over Europe has been determined for winter and spring. Basic idea is that the natural interannual snow cover fluctuations would be an estimate for a snow cover trend in case of a possible future European temperature trend. A statistical model originally developed for a similar investigation over Austria has been applied to Switzerland. Present data base has been the daily records of 59 Swiss stations between 273 and 3580 m a.s.l. for the years 1961 to 1990. The snow-temperature relation we find can be interpreted as follows: A rise in the European temperature by 1 degree should reduce the duration of snow cover in the Alpine elevations of Switzerland by up to 4 weeks in winter and 5 weeks in spring. This finding is similar to our earlier results for Austria except that the extreme sensitvity is located about 150 m higher in Switzerland than in Austria.

Zusammenfassung

Die Empfindlichkeit der Zahl von Tagen mit Schneedecke an Schweizer Klimastationen wurde gegen die mittlere Temperatur über Europa für Winter und Frühling bestimmt. Der Grundgedanke dabei ist, die natürlichen interannuellen Schwankungen der Schneedecke als repräsentativ für einen Trend der Schneedeckendauer bei einem möglichen zukünftigen Trend der Europatemperatur anzusehen. Ein statistisches Modell, das ursprünglich für gleichartige Untersuchungen über Österreich entwickelt worden ist, wurde jetzt auf die Schweiz angewandt. Die täglichen Messreihen (1961–1990) von 59 Schweizer Klimastationen, alle zwischen 273 m und 3580 m über Meeresniveau gelegen, bildeten die Datengrundlage. Die Schneetage-Temperatur-Beziehung, die wir hier finden, kann wie folgt interpretiert werden: Ein Anstieg der Europatemperatur um 1 Grad sollte die Dauer der Schneedecke um bis zu 4 Wochen im Winter und 5 Wochen im Frühling vermindern. Dieses Resultat ist ähnlich unseren früheren Ergebnissen für Österreich, außer dass die extreme Sensitivität in der Schweiz ungefähr 150 m höher gelegen ist als in Österreich.

1 Introduction

The seasonal snow cover fluctuates from year to year both in amount and duration. Likewise, the seasonal temperature fluctuates from year to year. These fluctuations represent climate variability, and both are coupled to each other. The snow cover as a function of global temperature has been a topic in climate theory since the models of BUDYKO (1969) and SELLERS (1969). Later studies have addressed the issue of snow pack at more regional scales, e.g. CAYAN (1996), WHETTON et al. (1996), and TOOMING and KADAJA (2000). Beniston (1997) concludes, on the basis of snow statistics over the last 50 years in the Swiss Alps, that temperature is the controlling factor for snow depth and duration. In a more recent work, BENISTON et al. (2003) focused on snow duration as a function of station height as well as of shifts in both winter mean temperature and precipitation. They found a strong linear relation between snow duration and height at intermediate levels. Further, the impact of the winter precipitation upon the snow cover duration was almost negligible as compared to the temperature impact.

These studies suggest that the snow cover duration at Alpine climate stations is predominantly controlled by the height of the station and by the seasonal climate as expressed through the temperature over Europe. The influence of other factors has been deliberately excluded from the present investigation. We shall follow the philosophy developed in a recent study by HANTEL et al. (2000) who designed a statistical model for Austrian climate stations. Their model was focused upon the sensitivity of the relative snow cover duration n with respect to what they called the *Alpine temperature* τ; the latter is a linear combination of the European temperature and the station height. We expect n to be zero for high τ (stations in a warm climate at low levels – "never snow"), and unity for low τ (stations in a cold climate at high levels – "always snow"). At intermediate levels the slope of the n-curve with respect to τ adopts an extreme value, referred to as the *sensitivity* of the snow duration relative to the Alpine temperature.

Moreover they found for Austrian climate stations that, for example, the sensitivity is -0.34/K in winter. They went on to hypothesize that the same relationship,

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albeit derived from seasonal fluctuations, should also be valid for longer-term climate changes. This would imply that a rise of European temperature by 1 degree would, for example, reduce the duration of the winter snow cover by 34 %, equivalent to 4 weeks.

The purpose of the present study is to apply this method to the independent Swiss data. Switzerland and Austria are neighbouring countries in the Alpine climate region; thus the parameters we expect for Switzerland should be not too much different from the equivalent parameters we found for Austria. At the same time we want to scrutinize the approach of HANTEL et al. (2000) and test its applicability.

2 Data

We have used the daily records of 59 Swiss stations between 273 and 3580 m a.s.l. for the years 1961 to 1990 from MeteoSwiss. From these stations 19 are situated below 500 m, 17 between 500 and 1000 m, 14 between 1000 and 1500 m, 6 between 1500 and 2000 m and 3 above 2000 m. More details can be found in WIELKE (2002).

The number N of snow days per season has been calculated through the parameter snow height. A snow height of at least 5 cm has been counted as a snow day. BENISTON (1997) considers snow depth thresholds from 1 cm up to 150 cm. Increasing the upper limit beyond 5 cm in our data set would have severely reduced the amount of available data. On the other hand, very small snow depths are problematic during melting periods. Thus a threshold of 5 cm has been chosen as a compromise. The values of N were normalized with the total number N_0 of days within the season (N_0=90 or 91 for winter, DJF, and 92 for spring, MAM). This yielded the relative snow cover duration n=N/N_0 of the season considered.

The seasonal *European temperature* T has been calculated from the gridded monthly temperature data set as provided by JONES (1994); it has been defined as the horizontal average over the array 5°–25°E and 42.5°–52.5°N and as the time average over the respective months. T is sufficiently close to what a climate model should predict for the large-scale temperature development representative for the seasons of Central Europe. The Jones data are anomalies of the reference temperature from 1961–1990; the reference temperature has no impact upon the results.

Before the data were processed by the statistical model we performed some rigorous quality checks, following the procedure described by HANTEL et al. (2000). This excluded about 40 % of the basic data; the eventual results were obtained with the corresponding reduced data set. However, when running the statistical model with the full data set we obtained practically the same results (see below). Further details of this component of the present study have been documented by WIELKE (2002).

3 Theory

The statistical model applied has been discussed in detail by HANTEL et al. (2000); only the main concept shall be reviewed here. We shall estimate the sensitivity for a single station *(local fit)* as well as the mean sensitivity representative for all stations *(global fit)*.

3.1 Local fit

The functional relationship between n at one single climate station and T cannot be linear throughout because n must asymptotically approach unity for low temperature and zero for high temperature. Therefore the data have been fitted by the following logistic curve:

$$n(T;s_0,T_0) = \frac{1}{2}\tanh[2s_0(T-T_0)] + \frac{1}{2} \tag{3.1}$$

the slope of which is:

$$s = \frac{s_0}{\cosh^2[2s_0(T-T_0)]} \tag{3.2}$$

The slope is negative everywhere and adopts, for the argument T=T_0, its negative maximum s=s_0. This is the parameter referred to as *sensitivity*.

We assume that the best estimates for the curve parameters s_0 and T_0, based on the given measurements of n and T, are those for which the weighted sum of squares of the deviations is a minimum (TAYLOR, 1997). We have to specify a priori where the unknown stochastic error might be. The fit is called *rectified* if the measurement error of the number of snow days is considered negligible compared with the temperature error. The opposite is called *nonlinear* fit. In case of the *extended* fit both data sets are treated with nonnegligible errors.

The cost function J_{LE} for the *local extended* fit can be written as

$$J_{LE}(s_0,T_0) = \sum_{i=1}^{I}\left[\left(\frac{n_i-n^i}{\sigma_i}\right)^2 + \left(\frac{T_i-T^i}{\chi_i}\right)^2\right] \tag{3.3}$$

The observed values are n_i and T_i, the values on the theoretical curve in Eq. (3.1) are n^i and T^i, the parameters σ_i and χ_i are the error variances. I is the number of years with available data for the local fit. The values on the theoretical curve are obtained as follows: The observed snow duration is inserted as n=n_i into Eq. (3.1) which then is solved for T to yield the model temperature T=T^i. Similarly, the observed temperature is inserted as T=T_i into Eq. (3.1) which is solved for n to yield the corresponding model snow duration n=n^i.

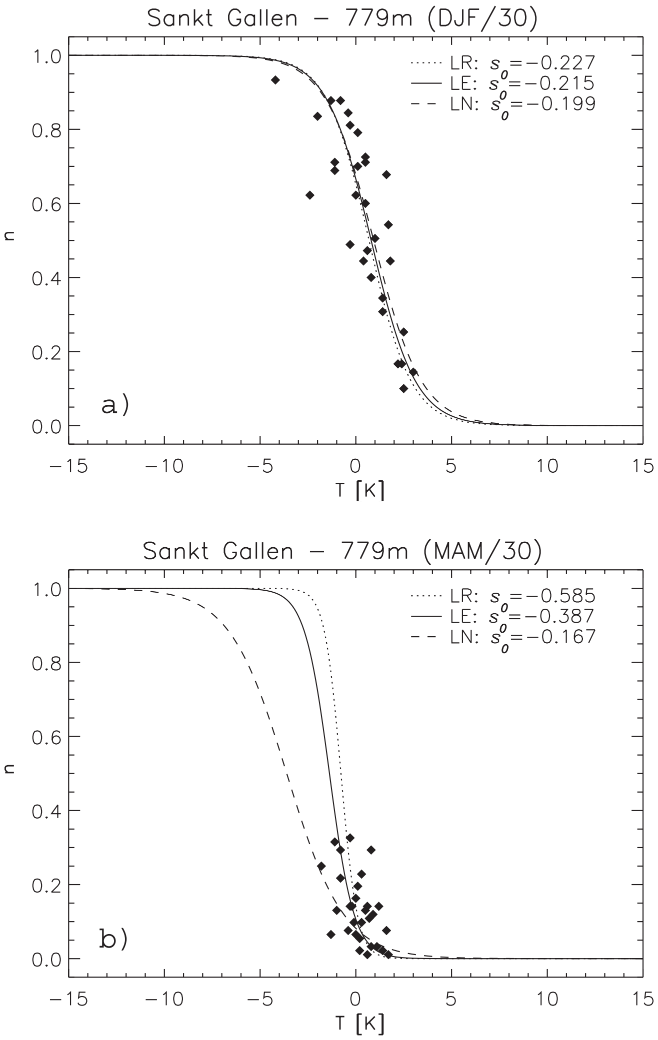

Figure 1: Local snow-temperature relationship: Relative duration of snow cover n as a function of the European temperature T for the station Sankt Gallen. Each point is valid for one individual year. The three curves represent the different fits, i.e. local rectified LR (broken line), local extended LE (full line) and local nonlinear LN (dashed line) fit: a) winter, b) spring. Sensitivity s_0 in units K^{-1}.

Fig. 1 shows the local snow-temperature relationship for a typical station, Sankt Gallen, in winter and spring. The sensitivity s_0 depends on the fit applied. For example, the local nonlinear (LN) fit in Fig. 1a yields a sensitivity of –0.20/K corresponding to a reduction of the relative duration of snow cover of about 20 % per degree warming. The local rectified (LR) fit yields –0.23/K. In spring (Fig. 1b) s_0 varies between –0.17/K and –0.58/K. Since the winter data are more evenly distributed over the snow duration interval than the spring data the estimate of s_0 is much less dependent upon the specific fit applied in winter than in spring, with the consequence that the winter results are more reliable than the spring results. We consider the local extended (LE) fit as the best compromise. For Sankt Gallen Fig. 1 yields an s_0 of –0.22/K in winter and –0.39/K in spring. We estimate the error of s_0 as a sixth of the difference between LN and LR, guided by the 3-σ criterion. In this case the error of s_0 is 0.01/K in winter and 0.07/K in spring.

3.2 Global fit

In order to make the sensitivity s_0 representative for an entire region the station records have been combined to a single dataset. To account for the station height H the reference temperature in Eq. (3.1) is eliminated through

$$T_0(H) = \gamma H + T_{00} \tag{3.4}$$

where γ is a temperature lapse rate and T_{00} can be considered as a reference temperature. The model defined in Eq. (3.1) now depends on the parameters s_0, γ and T_{00} which need to be fitted:

$$n(H,T;s_0,\gamma,T_{00}) = \frac{1}{2}\tanh[2s_0(T-\gamma H - T_{00})] + \frac{1}{2} \tag{3.5}$$

Defining the *Alpine temperature* $\tau = T - \gamma H$ allows us to plot n as function of τ, independent of H, for the entire region. HANTEL et al. (2000) noted that $\partial\tau(H,T)/\partial T$=1. Consequently, with $n(H,T)$=$n[\tau(H,T)]$, the slope as given is Eq. (3.2) is simply s=dn/dτ. Thus the sensitivity s_0 is also independent of the station height and has become a genuine Alpine climate parameter.

The slope of the function $n(\tau)$ adopts its extreme value s_0 at a mean height level $\overline{H}_{extr}$ for which the argument of the hyperbolic tangent in Eg. (3.5) vanishes. This level is characterized by $n = 0.5$ and defined as

$$\overline{H}_{extr} \equiv \frac{\overline{T} - T_{00}}{\gamma}. \tag{3.6}$$

$\overline{T}$ denotes the all year seasonal mean European temperature from the dataset of JONES (1994).

The cost function for the global fit has the same form as Eq. (3.3) as for the local fit except that it now depends on the three parameters s_0, γ and T_{00}. Further, I denotes the number of all years and all stations of Switzerland that passed the rigorous quality check mentioned above: 735 in winter and 784 in spring.

4 Results

Fig. 2 shows the results gained with the extended fit for Switzerland in winter and spring. Each dot represents one individual year of one single station. The scatter is relatively high in both seasons. Added in Fig. 2 are the curves for Austria (long dashed) found by HANTEL et al. (2000); we have shifted them by $\Delta\tau$=1.78 K ($\Delta\tau$=0.11 K) for winter (spring) so that they intersect at n=0.5. The sensitivity of the Switzerland curves is a bit less than of the Austria curves.

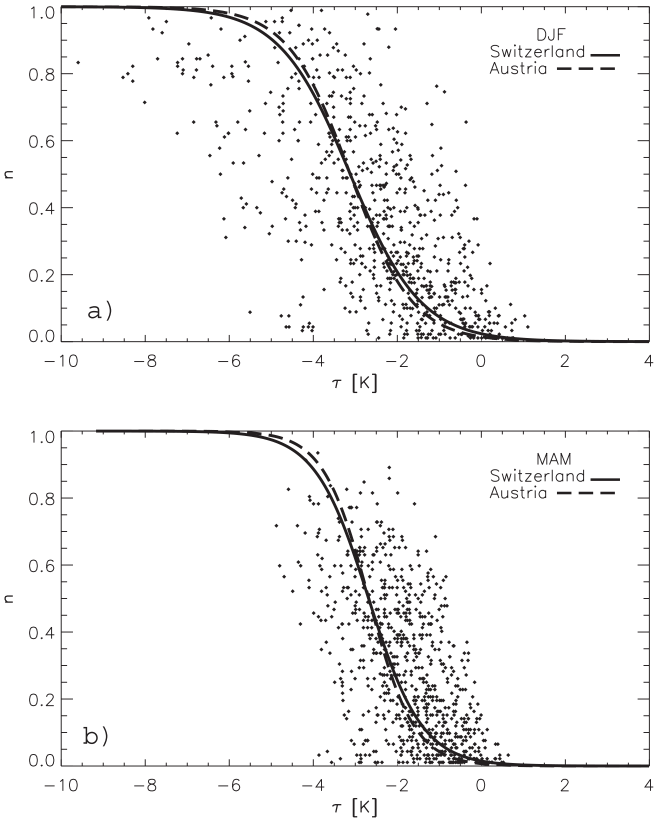

Figure 2: Fig. 2: Global snow-temperature relationship: Relative duration of snow cover n of all Swiss stations plotted against the Alpine temperature τ: a) winter, b) spring. The underlying parameters are taken from the global extended fit. $s_0 = -0.30$/K (-0.39/K) for Switzerland in winter (spring). Dashed line is the Austrian curve shifted by $\Delta\tau = 1.78$ K (0.11 K) in winter (spring).

The parameters are summarized in Tab. 1. The sensitivity of Switzerlands climate, i.e., the level of extreme slope of the snow duration-temperature curve, is observed in heights around 740 m (1460 m) during winter (spring). Above and below these heights the slope of the curve is less negative. This finding is much the same as our earlier results for Austria with the main difference that HANTEL et al. (2000) found the extreme sensitivity in heights around 580 m (1370 m) during winter (spring). These slightly lower levels as compared to Switzerland are presumably due to the slightly lower mean temperatures in Austria at the same elevations.

An important question is to what extent the results in Tab. 1 depend upon the parameters of the error model. The error variances σ_i and χ_i were specified a priori. In order to test the impact of these poorly known parameters HANTEL et al. (2000) varied their ratio over a large interval by multiplying σ_i with 10^{ν} and running ν from highly negative values (all errors are attributed to the n_i – the nonlinear fit) to highly positive values (all errors are attributed to temperature – the rectified fit). ν=0 is the standard choice, it corresponds to the extended fit. The equivalent experiment for the Swiss data is shown

Table 1: Global sensitivity s_0 and height $\overline{H}_{extr}$ at which the slope of the $n(\tau)$-curve adopts the value s_0, for Switzerland (CH) and Austria (A). s_0 determined with global extended fit.

	s_0 (K^{-1})		$\overline{H}_{extr}$ (m)	
	DJF	MAM	DJF	MAM
CH	-0.30 ± 0.06	-0.39 ± 0.19	740	1458
A	-0.34 ± 0.04	-0.46 ± 0.13	575	1373

in Fig. 3 for the four datasets of Fig. 2. s_0 changes by a factor of 2 in winter and by a factor of 5 to 15 in spring. This is in accord with the local result discussed in Fig. 1 which suggested that the fit in winter is more reliable than in spring.

In a further sensitivity experiment we relaxed the rigorous quality checks cited above and kept all available Swiss snow duration data in our evaluation, no matter if dubious or not. This increased the scatter in the plot corresponding to Fig. 2 (not shown) but altered our results for the global fit only slightly: $s_0 = -0.32$/K compared to -0.30/K ($s_0 = -0.42$/K compared to –0.39/K) in winter (spring) in Tab. 1. HANTEL et al. (2000) had found the same robustness in their Austrian data set.

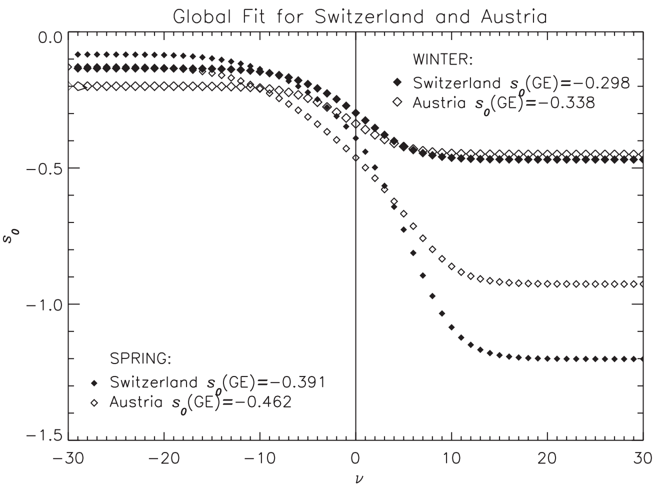

Figure 3: Local snow-temperature relationship: Relative duration of snow cover n as a function of the European temperature T for the station Sankt Gallen. Each point is valid for one individual year. The three curves represent the different fits, i.e. local rectified LR (broken line), local extended LE (full line) and local nonlinear LN (dashed line) fit: a) winter, b) spring. Sensitivity s_0 in units K^{-1}.

5 Discussion and conclusions

The present study is the extension of a method originally developed by HANTEL et al. (2000) for Austrian climate stations. Here we have briefly reviewed the theoretical concept and have applied the method to the independent data of Switzerland. Basic idea of the method has been to plot the seasonal snow cover duration n of a climate station versus the Alpine temperature τ (equal to the European temperature T minus the weighted station height H); the possible influence of other factors like station precipitation or radiation has been disregarded. The present application has corroborated our earlier result that this plot resembles a logistic curve. Its slope $dn/d\tau = \partial n(H,T)/\partial T$ is negative throughout and becomes extreme for the relative snow cover duration n=0.5. We have called this value the global sensitivity of the snow-temperature relationship. We have again demonstrated here that the method is sufficiently robust against errors of the input data and ambiguities in the parameters of the statistical model.

Climate changes have different modes like, for example, fluctuations and trend. Can we gain, from interannual fluctuations, a statement for the trend? HANTEL et al. (2000) have argued that, given the standard deviation of 1.5 K for T, a climate shift of 1 K would be within the natural seasonal fluctuations.

By interpreting our results in this way, they imply that a rise in the European temperature by 1 degree has the potential to reduce the relative duration of snow cover in Switzerland in the elevations of extreme sensitivity by 30 % or 4 weeks during winter and by 39 % or 5 weeks during spring. Above or below of these elevations the sensitivity is gradually getting smaller. The extreme sensitivity of Switzerland is observed at elevations around 740 m (1460 m) during winter (spring). Our earlier analysis for Austria had shown similar behaviour (4 weeks reduction per degree warming in winter and 6 weeks in spring), with the extreme sensitivity at elevations around 580 m (1370 m) during winter (spring). For spring we have found a potential reduction of 39 % (5 weeks) for Switzerland and 46 % (6 weeks) for Austria; both figures coincide satisfactorily. Nevertheless, the data robustness is weaker in spring than in winter; thus the spring results should be interpreted with particular caution.

In summary, our snow cover duration-Alpine temperature relationship, gained from natural interannual fluctuations, can be applied to a possible future climate trend. The sensitivities we have found are almost equal for Switzerland and Austria. Thus they deserve credence as a result relevant for the entire Alpine region.

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