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Warm winter spells in the Swiss Alps: strong heat waves in a cold season? A study focusing on climate observations at the Saentis high mountain site

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Abstract

Investigations conducted for several Swiss mountain climatological sites, and in particular the Saentis high mountain site at 2,500 m above sea level, show that positive temperature anomalies during the winter season currently exceed those of all other seasons. These “heat waves” exhibit daily maximum temperature anomalies sometimes in excess of 16°C, and are observed to have increased substantially since the late 1960s. These events are related to the North Atlantic Oscillation (NAO) that exerts significant controls on snow cover and surface-atmosphere temperature feedbacks in the alpine region. A glimpse to the future is provided for the period 2071-2100, based on regional climate model simulations which suggest that warm winter spells may increase by 30%. The impacts of such events, particularly in terms of snow and water availability and the mountain economies that depend on these resources, need to be incorporated into future strategic resource and economic planning in the Alps.

Introduction

Severe heat waves, such as the recent event that affected many parts of Europe from June through August 2003 (Beniston, 2004; Schär et al., 2004), are often accompanied by adverse social, environmental and economic consequences. During the 2003 heat wave, parts of Switzerland such as in Basel (367 m above sea-level in northern Switzerland) experienced monthly maximum temperature anomalies, based on the 1961-1990 climatological average period, of over 6°C in August (Beniston, 2004). On a single-day basis, exceedances over the 30-year average daily mean reached 9.3°C in Basel and 11.5°C at the high elevation site of Saentis (2500 m above sea-level in north-eastern Switzerland).

While such summer heat waves are indeed characterized by large departures of maximum temperatures from their mean values, these anomalies are smaller than those observed in winter at high elevations in the Alps in the last quarter of the 20th century. Daily maximum temperature anomalies (hereafter referred to as Tmax) during winter have been observed to exceed 15°C at sites such as Saentis, Grand-Saint-Bernard (altitude: 2479 m) or Jungfraujoch (altitude: 3572 m), for example, with exceedances of 10°C and more commonly occurring in the last 2-3 decades.

Such large anomalies in winter cannot be appropriately referred to as heat waves, because they do not correspond to the traditional image that the public has of such an event, commonly believed to be associated with the summer season. Periods with strong positive temperature exceedances in winter will thus be referred to here as “warm winter spells”. While these spells are generally not perceived to be as extreme as summer heat waves, they are in a statistical sense even more extreme and can have adverse environmental and socio-economic impacts too. These winter spells will be shown here to have increased substantially in the 20th century.

Data

Beniston (2004) has shown that the quality and homogeneity of daily weather data recorded at numerous Swiss locations is appropriate for conducting in-depth studies. Tmax data for each day of the year has been averaged over the 1961-1990 reference period in order to compute daily anomalies. In the following sections, the focus will be on Tmax exceedances beyond particular temperature thresholds above the mean values of a given day (e.g., +5°C and +10°C beyond the mean). In order to remove the arbitrariness of fixed thresholds, however, analyses based on quantiles of the Tmax probability density functions (PDF) have also been conducted.

Data from 10 Swiss climatological stations have been analyzed in this study, and Table 1 provides the correlation coefficient between the available daily Tmax anomaly at a given site and the Saentis data. The high value of the coefficients bears witness to the fact that anomalies and their trends are very similar across the different sites. For reasons of conciseness, therefore, only the Saentis data will be discussed here, but the conclusions hold for the other locations as well.

The climate scenario data has been obtained from one of a number of model simulations that have been applied to the 2071-2100 time-frame in the context of the EU “PRUDENCE” project (Christensen et al., 2002). Two thirty-year climate simulations have been undertaken for Europe, for the 1961-1990 “current climate” control period, and the 2071-2100 future period. The boundary and initial conditions for the regional climate model (RCM) simulations are provided by general circulation models (GCM), based on the fully-coupled HadCM3 ocean-atmosphere GCM (Johns et al., 2003) that drives the higher-resolution atmospheric GCM HadAM3H (Pope et al., 2000). The GCMs simulate the response of global climate over the entire 21st century to a range of greenhouse-gas emission scenarios developed by the Intergovernmental Panel on Climate Change (IPCC; Nakicenovic et al., 2000), of which only one will be used here, namely the IPCC A-2 Scenario. This scenario assumes low priorities on greenhouse-gas abatement strategies and high population growth in the developing world, leading to atmospheric CO_2 levels in excess of 850 ppmv by 2100, compared to 370 ppmv in 1990. Other emission futures that assume a larger degree of technological, political, and legislative measures designed to abate emissions, result in lower concentrations and a weaker climatic response. In this study, it was of interest to investigate the changes that may occur under the highest set of CO_2 emissions in order to assess the shifts in warm winter spells under a "worst-case climate scenario".

The regional models, driven by the initial and boundary conditions of the HadAM3H GCM, provide a measure of regional detail concerning the response of climate in the European area to a changing global climate; their higher spatial definition allows an improved resolution of features such as coastlines and topography that are important determinants for regional climates. Among these RCMs, the HIRHAM4 model (Christensen et al., 1998) of the Danish Meteorological Institute has shown reasonable skill in reproducing observed temperature patterns over Europe (e.g., Beniston, 2004). The RCM results from this model will be used in the discussion on future trends in warm winter spells.

Results and discussion

Figure 1 illustrates the total exceedances per decade of daily Tmax for thresholds of 5°C and 10°C above the mean at Saentis in each of the four seasons of all decades of the 20th century. For all counts, the winter exceedances are larger than in the other seasons since the 1970s, and more obviously so for the 10°C threshold. The upward tendency throughout the 20th century is a reflection of the general warming trend in the Alps that affect both low and high elevations in a similar manner, as Beniston and Rebetez (1996) and Girogi et al. (1997) have shown for Switzerland. Temperatures at Saentis and the other high altitude stations have risen by over 1.5°C since 1900, which is as large as the rates of change observed at low-elevations, e.g., Zurich (569 m above sea-level) or Lugano (276 m). There is no evidence of reduced warming due to altitude in the Swiss Alps, and indeed the rate of warming observed in the 20th century is more than double the global-average figure (Beniston et al., 1997).

The mid-century warm springs and summers are well captured in the figure for 5°C threshold exceedance, where the late 1940s were the warmest years in Switzerland prior to the record-breaking 2003 heat wave. The mid-century warm event does not appear in the exceedance counts for the 10°C threshold Tmax, however, which implies that lower exceedance levels but higher persistence were responsible for the warm summers of the 1940s. Winter Tmax for the 10°C threshold increase sharply from 0 or 1 days per decade that are observed prior to the 1970s, to over 20 days in the 1990s. In no other season is there such a remarkable increase in the number of strong temperature anomalies. Figure 2 shows the average maximum Tmax anomaly for each season per decade at Saentis, to illustrate that winter anomalies have increased by over 5°C since 1900 and have remained consistently above those of the other seasons since 1970.

The IPCC (2001) has defined the 90% quantile level as the threshold beyond which temperatures enter into their "extreme" domain, in a statistical sense. Analyses of 90% and 99% quantiles of Tmax at Saentis confirm the findings based on fixed thresholds, and Table 2 summarizes the decadal changes of these two quantiles, based on differences between the 1901-1910 decade and each subsequent decade. The data have been detrended, so that the changes between the beginning and end of the 20th century are related to shifts in the variability of temperature, and not simply the result of a bias imposed by a warming climate during this period. The decadal differences vary from one season to another, but the clearest trend emerges in the winter quantiles, whose 90% and 99% quantiles increase regularly from one decade to another to attain respectively 4.3°C and 5.0°C more in the 1990s compared to the 1901-1910 average. The other seasons exhibit more inter-decadal variability and quantile values are generally around 2.5°C higher at the end of the 20th century compared to the first decade. Winters in the Alps have thus clearly warmed much more rapidly than any of the other seasons, with a consequent increase in the potential for more frequent, intense, and persistent warm winter spells.

The disproportionate increase in strongly positive Tmax anomalies in the Alps observed since the 1970s in winter, compared to other seasons, is related to a number of concurring factors that include the sharp increase in the number of persistent anticyclonic weather patterns that have affected the alpine region since the late 1960s. These have been shown *inter alia* by Hurrell (1995), Rogers (1997), and Beniston and Jungo (2002) to be linked to the positive or warm phase of the North Atlantic Oscillation (NAO). The persistence of high pressure (exceeding a sea-level reduced pressure threshold of 1030 hPa) in Switzerland has more than doubled between the 1960s (14 days per winter) and the 1990s (31 days) according to pressure records from the representative sites of Bern and Zurich. These persistent winter high pressure cells are accompanied to positive temperature anomalies and lower than average winter precipitation, since storm tracks tend to be routed far to the north of the Alps. The amount and duration of snow cover in the alpine forelands have thus been significantly reduced in the last quarter of the 20th century compared to earlier decades, as shown by Beniston et al. (2003). As a consequence, the negative temperature-albedo feedback between snow cover and alpine temperatures is less marked during the positive phase of the NAO. Snow cover on the ground has diminished from an average of 43 days per winter in the 1960s in Bern to 22 days per winter in the 1990s; while in Lugano (south of the Alps) snow cover has diminished from 15 days per winter in the 1960s to less than 3 in the 1990s. The direct and indirect influence of the highly-positive NAO phase on the alpine region has resulted in strong positive temperature feedbacks, and thus to larger mean and extreme trends of Tmax in winter compared to the other seasons.

Figure 3 relates the NAO index (computed as the normalized pressure difference between Iceland and the Azores) to the number of exceedances beyond the 5°C threshold over the mean at Saentis. Two distinct and sharply contrasting periods are observed in this figure, prior to 1970 where the relation between threshold exceedance and the NAO index is negative and an inverse relation since the beginning of the 1970s. The significance of the regression lines is high in both cases,i.e., r=0.75 for the period 1901-1970 and r=0.92 for 1971-2000 The particularly strong controls on warm winter spells by the NAO in the latter part of the 20th century enables the NAO Index to be used as an empirical predictor of these events. The change in the slope that is observed to occur around 1970 can be explained by the fact that earlier in the 20th century, the NAO was not necessarily in phase with pressure, temperature, and precipitation patterns in the Alps as it has been in the more recent decades. Consequently, a same value of the NAO index may be associated with different circulation patterns, resulting in different controls on the occurrence and persistence of warm winter spells. Furthermore, the negative slope is linked to a low number of warm winter spells (<8 per year) as opposed to the positive slope, that is associated with a high number of events (>10 and up to 25 per year).

The HIRHAM4 RCM simulations for the 2071-2100 period have been analyzed to quantify possible changes in warm winter spells, but prior to that model quality checks have been undertaken to in order to assess the model's capability in reproducing observed climate. Figure 4, for example, shows the cumulative distribution of observed and simulated winter-average Tmax for the reference climatological period 1961-1990 averaged over the four model grid-points centered on Saentis. An adiabatic adjustment has been applied to the model data to allow for the altitudinal difference between the model grid points and reality. The model reproduces the observations to within about 0.7°C for the 30-year average, but the variance of the modeled distribution is somewhat lower in the RCM. As a result, the model tends to underestimate the upper extremes of the temperature range; for example, the 90% quantile is about 1°C lower in the simulated data compared to observations. These discrepancies can be corrected to some extent by adjusting the computations of threshold exceedance in the model such that exceedances beyond the 5°C and 10°C thresholds are simulated to within less than 10% of observations. Table 3 provides the ratio of future to current exceedances in order to illustrate the changes that may occur in 2071-2100 compared to the reference period 1961-1990 according to the HIRHAM4 RCM simulations. As for the 20th century, winter stands out as the season with the highest frequency of exceedance, with a 30% increase projected to occur for both the 5°C and 10°C thresholds. In addition, maximum wintertime Tmax anomalies are simulated to exceed 18.5°C (as compared to 16.2°C in 1998, for example), in a climate that is projected to warm on average by 4°C in winter in Switzerland under the IPCC A-2 greenhouse-gas emissions scenario. It is expected that for the lower emission scenarios, such as B-2, the overall increase of warm winter spells would be lower than those that are related to the A-2 scenario.

These results need to be viewed with caution, however, because the model simulations do not necessarily incorporate all the intricacies of a changing climate, such as the future behavior of the NAO in a warmer climate. As seen in Figure 3, the NAO can be used within limits as a predictor of warm winter spells, but its relation to these spells tends to "flip" in time as seen around 1970. Because GCMs currently have difficulty in reproducing and predicting NAO behavior, the relationship between the NAO and warm winter spells in the future remains highly uncertain. There is speculation, based on the observations of the latter part of the 20th century, that a warmer climate may result in a frequently-positive NAO mode, thereby influencing the warm winter spells in a similar manner to that observed since the early 1970s.

Conclusions

This paper has focused on the occurrence of strong positive temperature anomalies in the Swiss Alps, drawing on data from the Saentis climatological observing station as a site representative of many other high mountain sites. It has been shown that the marked increase in these events since the 1970s is related to the persistent and strongly-positive phase of the North Atlantic Oscillation. According to one set of RCM simulations, warm winter spells are likely to increase in the future as climate responds to increased atmospheric concentrations of greenhouse gases.

Warm winter spells in the Alps are, in a statistical sense, strong heat waves that occur during the coldest period of the year. When these spells do occur, they are not perceived in the same way as summer heat waves that have discernible effects on health, natural ecosystems, agriculture, water supply, energy demand, etc. However, warm winter spells have significant impacts on many environmental and socio-economic systems, particularly if temperatures exceed the freezing point for any length of time, since this results in snow-melt, sharply reduced seasonal snow cover, enhanced avalanche risk for exposed slopes, early runoff into river basins that originate in the mountains, perturbations to the growing period of alpine vegetation, reduced income for alpine ski resorts, and changes in hydro-power supply because of seasonal shifts in the filling of dams, to mention but a few possible consequences. The projected increase of warm winter spells in a warmer climate will require a careful assessment of the manner in which snow and hydrology will be affected in the future, as these are important resource bases for the Swiss economy. The concerns raised by the impacts of severe summer heat waves, such as the event that affected much of Europe in 2003, should not overshadow the very real impacts of winter warm spells that have occurred in the past and will increasingly be seen in the future if climate warms to the extent projected by recent climate model simulations.

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Table Captions

Table 1: Correlation between Saentis temperature records and 10 other high-elevation sites in the Alps

Table 2: Decadal-scale changes in 90% and 99% quantiles of maximum temperature at Saentis with respect to the 1901-1910 decade for each season.

Table 3: Ratio threshold exceedances (mean + 5°C and mean + 10°C) at Saentis for the period 2071-2100 compared to the period 1961-1990, for both the IPCC A-2 and B-2 Scenarios.

Figure Captions

Figure 1: Exceedances per decade of maximum daily temperature at Saentis (2500 m above sea-level, eastern Switzerland) for thresholds of mean + 5°C and mean + 10°C for each season during the course of the 20th century.

Figure 2: Average maximum exceedance of Tmax per decade and season at Saentis.

Figure 3: Links between the NAO index and the frequency of threshold exceedance of wintertime Tmax (mean + 5°C). Diamonds refer to the winters from 1901-1970, squares to the period 1971-2000.

Figure 4: Comparisons of the cumulative distribution of winter Tmax as observed during the 1961-1990 period and as simulated by the HIRHAM4 regional climate model.

Correlation between Saentis (2,500 m above sea level) and:

Arosa (1,847 m)	0.95
Château d’Oex (980 m)	0.89
Davos (1,590 m)	0.89
Einsiedeln (910 m)	0.89
Gd. St. Bernard (2,479 m)	0.92
Jungfraujoch (3,572 m)	0.94
Montana (1,495 m)	0.92
Sta. Maria Müstair (1,390 m)	0.84
Scuol (1,295 m)	0.87
Zurich (569 m)	0.85

Decade	Winter Q90	Winter Q99	Spring Q90	Spring Q99	Summer Q90	Summer Q99	Autumn Q90	Autumn Q99
1901-1910	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1911-1920	0.4	0.1	0.7	0.4	0.1	-0.3	-0.7	-0.3
1921-1930	0.4	0.2	1.8	1.0	1.2	1.8	1.5	1.2
1931-1940	1.0	1.0	0.3	0.3	1.1	0.8	0.5	1.1
1941-1950	0.8	1.0	2.2	1.6	2.4	2.4	1.8	1.7
1951-1960	1.0	1.3	1.8	0.9	1.5	2.0	1.2	1.2
1961-1970	1.3	1.7	0.5	0.0	2.0	2.0	3.4	3.6
1971-1980	2.4	3.6	0.6	0.2	1.1	1.4	2.4	2.8
1981-1990	2.6	3.5	1.3	0.3	1.6	1.8	4.1	4.4
1991-2000	4.3	5.0	2.0	1.5	2.5	2.6	2.8	2.8

	Exceedance beyond mean +5°C	Exceedance beyond mean +10°C
Winter (DJF)	1.27	1.30
Spring (MAM)	1.01	1.25
Summer (JJA)	0.95	1.26
Autumn (SON)	0.96	0.96

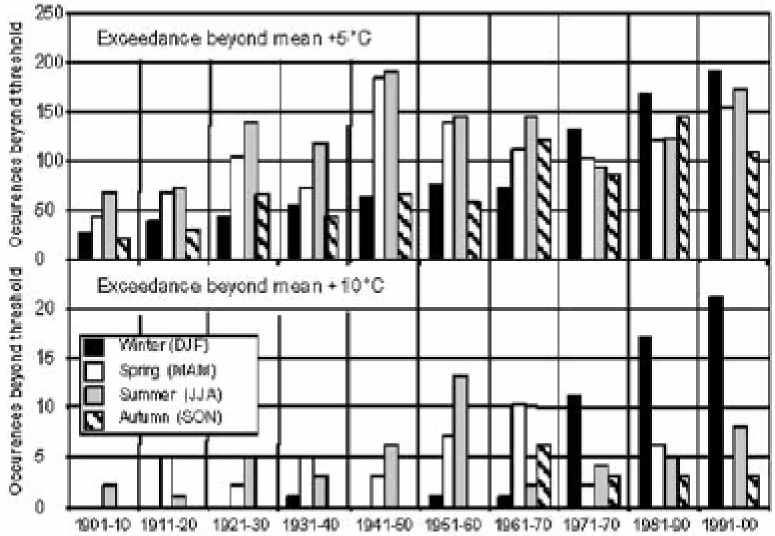


Figure 1. Exceedances per decade of maximum daily temperature at Saentis (2500 m above sea-level, eastern Switzerland) for thresholds of mean + 5°C and mean + 10°C for each season during the course of the 20th century.

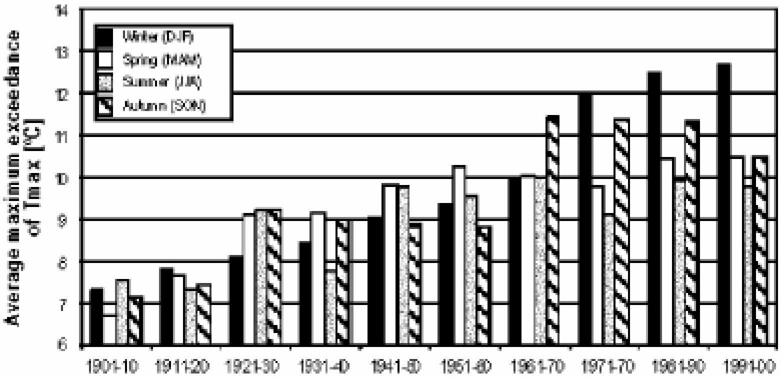
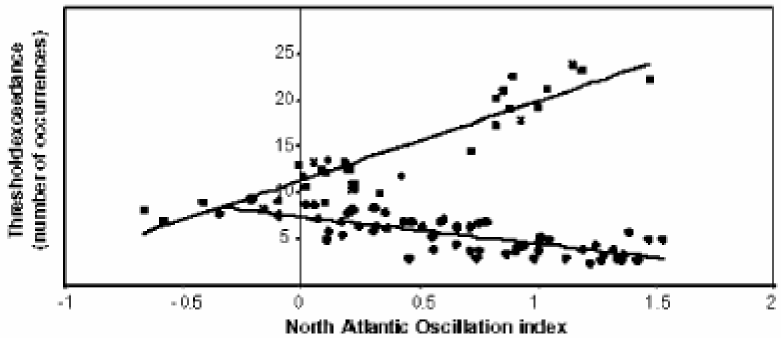


Figure 2. Average maximum exceedance of Tmax per decade and season at Saentis.



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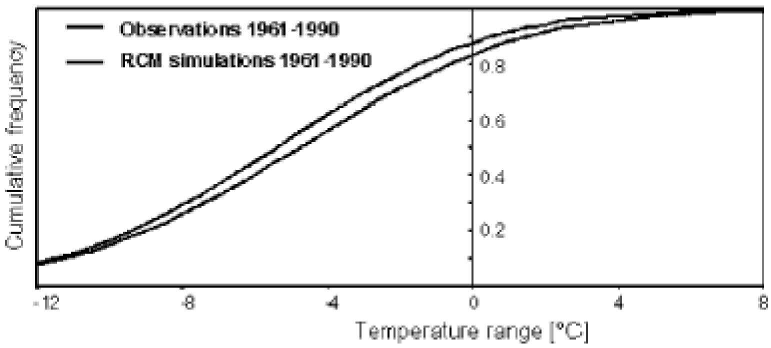

Figure 4. Comparisons of the cumulative distribution of winter Tmax as observed during the 1961 – 1990 period and as simulated by the HIRHAM4 regional climate model.