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Changes in variability and persistence of climate in Switzerland: Exploring 20th century observations and 21st century simulations

Martin Beniston *, Stéphane Goyette

Chair for Climate Research, University of Geneva, Switzerland

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Abstract

This paper investigates the shift in variance under conditions of atmospheric warming, under the paradigm that a warmer climate induces greater variability, as has been suggested by a number of other studies. Based upon observational data since 1900 at both a low and a high elevation site in Switzerland it is shown that, at least for these locations, the inter-annual and decadal variability of both maximum and minimum daily temperatures has in fact *decreased* over the course of the 20th century despite the strong warming that has been observed in the intervening period. The decrease in climate variability is attributed to changes in daily weather conditions as well as these aggregated in weather types, with an observed reduction in the more perturbed weather types and an increase in the weather patterns that exhibit greater persistence, particularly since the 1960s and 1970s. The greater persistence recorded in daily weather conditions associated with more elevated pressure fields helps to explain the decrease in variability during a period where minimum and maximum temperatures have been observed to rise considerably since 1900. An insight into the future behavior of temperature variability in Switzerland, based on the daily results of a regional climate model applied to the IPCC A-2 emissions scenario (a high greenhouse-gas emissions scenario leading to strong climate forcing during the 21st century) suggests that a warmer climate may induce greater variability in maximum temperatures, but also greater persistence beyond selected thresholds; in the case of minimum temperatures, variance remains close to current conditions in the latter part of the 21st century, but the persistence of cold events diminishes substantially, as can be expected in a climate that is estimated by the climate model to warm by about 4 °C on average in Switzerland.

Keywords: climate variability; weather extremes; regional climate modelling; statistics

1. Introduction

It has been assumed in numerous investigations related to climatic change that a warmer climate may also be a more variable climate (e.g., Katz and Brown, 1992; IPCC, 2001; Schär et al., 2004); such statements are often supported by climate model results, as for example in the analysis of GCM and or RCM simulated temperature and precipitation (Mearns et al., 1995; Mearns et al., 1990) or in multiple-model simulations over Europe (e.g., Beniston et al., in press). However, the magnitude of variability varies significantly between different models (Räisänen, 2002) and it has been found that changes in variability in simulated temperature and precipitation could greatly differ from season to season as noted by Gregory and Mitchell (1995), Buishand and Beersma (1996), Giorgi and Francisco (2000), and Boer et al. (2000). In terms of the extremes of temperature, for example, many of these studies have suggested that shifts in the intensity and/or the

* Corresponding author.
E-mail address: martin.beniston@unige.ch (M. Beniston).

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frequency of the hot and cold tails of the probability density function (PDF) of temperature are likely to be associated more with changes in the variance than changes in the mean temperature (e.g., IPCC, 2001). This concept is illustrated schematically in Fig. 1, where Fig. 1a shows how a change in mean temperature and a shift of the temperature PDF leads to a drop in the extreme cold events but a rise in the occurrence of extreme warm events. Fig. 1b, on the other hand, highlights the fact that if the change in mean is accompanied by an increase in the variance of temperature, then the corresponding increase in extreme warm events is even larger than seen in Fig. 1a. Issues of scale and location related to the probability distribution functions are discussed in an overview paper by Ferro et al. (2005).

Numerous factors contribute to climatic variability on decadal to century time scales, of which five can be mentioned here, namely the random variability inherent to the atmosphere (where no external forcing occurs), the forced variability in the atmosphere–ocean system (NAO, ENSO, etc), solar variability, volcanic dust and other aerosol loading of the atmosphere, and the variability in trace gas concentrations (Rind and Overpeck, 1993). The increased atmospheric content of greenhouse gases of anthropogenic origin, in conjunction with the increase of sulfate aerosols, has resulted in a globally-averaged temperature increase 0.5 ± 0.2 °C during the 20th century (IPCC, 2001). If a warming climate is indeed accompanied by more variability, then it would follow that severe heat waves are likely to become commonplace, as reported by several studies following the 2003 heat wave that affected much of Europe from May to August of that year based on regional climate modeling studies (e.g., Beniston, 2004; Beniston, 2005; Christensen et al., 2002; Schär et al., 2004; Schär and

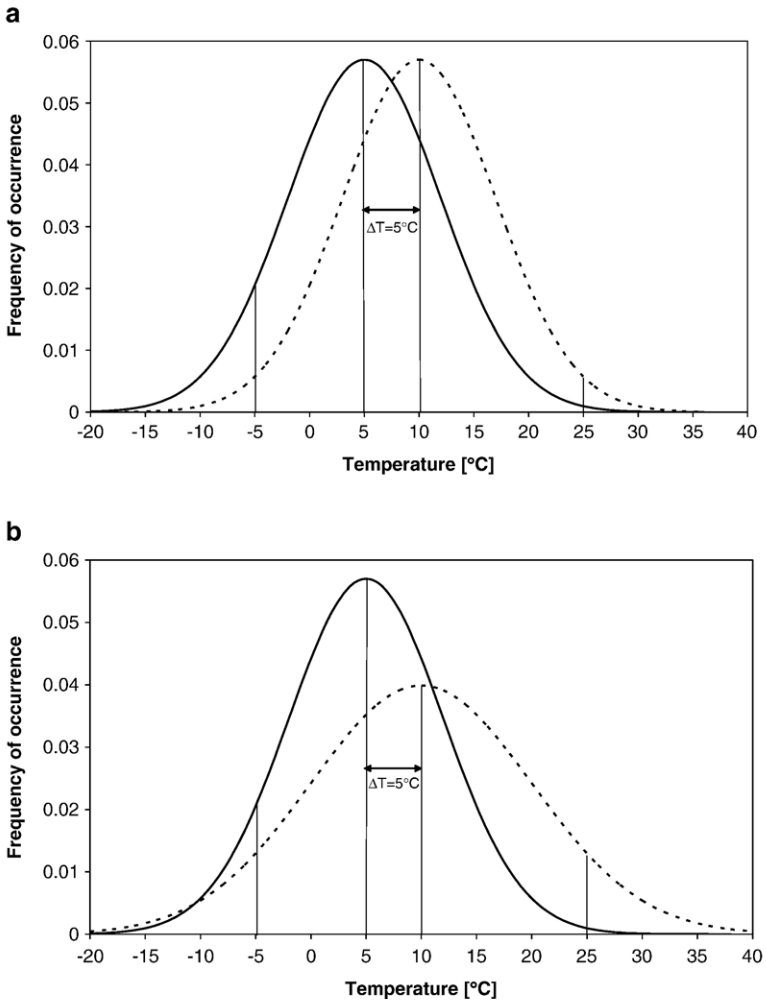

Fig. 1. Schematic diagram illustrating the shifts in extremes that can occur under changing mean conditions, through either a symmetrical change in the probability density function (PDF) of temperature (a), or through a shift in PDF where the variance and the kurtosis of the distribution changes (b).

Jendritzky, 2004). In view of the severity of the impacts related to the heat wave, in particular a large number of excess deaths (WHO, 2003), and other consequences of extremes such as river flooding increase (Ludwig et al. 2004), changes in seasonal discharge in major rivers (Graham, 2004; Middelkoop et al., 2001; Kwadijk and Rotmans, 1995; Arnell, 1999) with implications for hydro power (Lehner et al., 2005), stress on agriculture and food supply (Olesen and Bindi, 2002), and destruction of vast tracts of forested land in many parts of Europe, the risks associated with a warming and more variable climate warrant serious attention.

In view of the generally-accepted notion that a warmer climate may also be a more variable climate, it is of interest to investigate whether, based on long time-series of observational data, this hypothesis is indeed verified in a climate that has experienced a warming of 2 °C or more at certain locations in Switzerland since the beginning of the 20th century. While this rate of warming is less than what some models are suggesting for the end of the 21st century in a climate forced by high atmospheric greenhouse-gas concentrations (e.g., Beniston, 2004, 2005; Beniston et al., in press), the 20th-century warming in the Alpine area is 2–3 times greater than the global average (Jungo and Beniston, 2001) and provides an observational framework that allows to address the issue of links between mean temperature and its variance.

This paper investigates the trends in means, variability and persistence of climate at both low and high elevation sites in Switzerland in order to provide some answers to the questions posed and show that commonly-accepted assumptions are, somewhat surprisingly, not necessarily fulfilled, at least in the Alpine region. Section 2 will provide a brief overview of the data sets and model simulations used, while Section 3 will review the observational data to detect the possible changes in variability from 1900–2004 in relation to the warming that has occurred in the intervening period. Section 4 will focus on some of the large-scale processes that are responsible for the observed changes in variability and persistence. Prior to the Conclusions, Section 5 will compare a regional climate model simulation with observed data to assess the model's capacity in reproducing current variability and persistence for the 1961–1990 climatological reference period, and how these features of climate may change in a "greenhouse climate" for the period 2071–2100.

2. Observational and simulated data sets

The high quality of observational data in Switzerland, in terms of homogeneity and continuity in time (Begert et al., 2003), and the fact that it is available on a daily basis in digital form since 1901 (Bantle, 1989) for many sites, makes this an ideal locale for climate investigations requiring long time-series of data.

The observational data for this investigation makes use of two Swiss sites representative of low elevations (Basel, 369 m above sea level) and high elevations (Saentis, 2500 m above sea level). The results of the study are restricted to these two locations because they have proven their quality in a number of previous studies (Jungo and Beniston, 2001; Beniston and Jungo, 2002; Beniston and Stephenson, 2004; Beniston and Diaz, 2004) and the conclusions reached here also apply to most of the other Swiss sites. It is of interest to distinguish climatic characteristics at low and high elevations in order to highlight some differences in climate statistics that are associated with site characteristics, for example the influence of wintertime temperature inversions on temperatures at low elevations or the fact that a high elevation site is often closer to conditions of the "free atmosphere" and thus less subject to low-level boundary-layer influences.

The daily weather charts and daily climatological data available in digital format managed by the Swiss weather service (MeteoSwiss; Bantle, 1989; Begert et al., 2003) have been used in this study. In addition, the NCEP-NCAR data set has provided an additional observational framework for parts of this study.

In terms of numerical simulation of the climate system, a suite of regional climate models (RCMs) have been applied to the investigation of climatic change over Europe for the last 30 years of the 21st century in the context of a major EU project (the "PRUDENCE" project, described by Christensen et al., 2002), enabling changes in a number of key climate variables to be assessed. The different model simulations broadly agree on the magnitude of change in mean, maximum, and minimum temperatures; for example, Deque (2003) has highlighted the clustering of model results that constitutes one measure of the reliability of the regional-scale simulations. The HIRHAM regional climate model (RCM) of the Danish Meteorological Institute (Christensen et al., 1998) has been applied to the present investigation; its results compare well with those of the other RCMs used in the context of "PRUDENCE". Simulations of the reference climatic period 1961–1990 have shown that HIRHAM exhibits skill in reproducing contemporary climate (e.g., Beniston, 2004), thereby providing some measure of confidence for future climate simulations. The model has been applied to Europe at a 50-km resolution for both "current climate" simulations (the reference 1961–1990 period), and one realization of a "greenhouse climate" for the period 2071–2100, using the IPCC SRES A-2 scenario (Nakicenovic et al., 2000). The A-2 scenario assumes a high level of emissions during the course of the 21st century, resulting in atmospheric CO_2 levels of about 800 ppmv by 2100 (i.e., roughly three times the pre-industrial values of CO_2). This particular emissions future yields a strong climate response by 2100, within the upper range of possible global warming published by the IPCC (2001). The fully-coupled ocean–atmosphere general circulation model (GCM) of the UK Hadley Centre, HADCM3 (Johns et al., 2003) has been used to drive the higher-resolution atmospheric HadAM3H model (Pope et al., 2000), that in turn provides the initial and boundary conditions for the HIRHAM model.

3. Observed changes in means, variability and persistence

The changes in annual minimum temperature (Tmin) anomalies at Basel and Saentis during the course of the 20th century (1901–2004 inclusive), are shown in Fig. 2a, based on the 1961–1990 averages; the term anomaly is used in this paper to refer to the departure of an annual or seasonal mean from its corresponding 30-year climatological-average value computed for the 1961–1990 timeframe. A 5-point moving average computed with seasonal values has been applied to the time series to remove high frequency noise and thereby enable longer-term trends to emerge more clearly. Despite a number of decadal-scale oscillations, linked to the behavior of the North Atlantic Oscillation

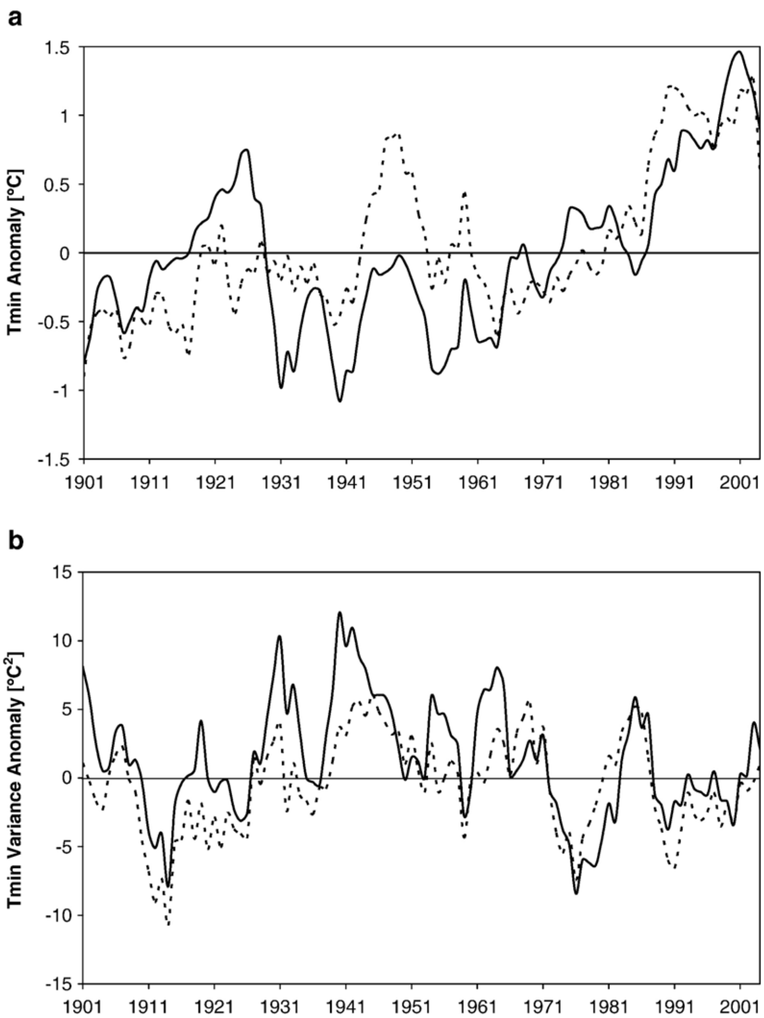

Fig. 2. Time series of minimum temperature anomalies (a) at Basel (solid line) and Saentis (dashed line) and minimum temperature variance anomalies (b) from 1901–2004. A 5-point filter has been applied to remove the noisiness of interannual variability.

(Wanner et al., 2001; Hurrell, 1995; Beniston and Jungo, 2002), the linear warming trend over the century exceeds 1.2 °C for both time series, with differences between the minimum and maximum peaks of the record close to 2 °C for Saentis and 2.5 °C for Basel (R^2 is 0.27 at Basel and 0.5 at Saentis, which is significant at the 95% level). Although there are differences in the two sets of anomaly series, related to site characteristics as mentioned in the previous section, they are on the whole in phase with major features such as the mid-century warm period or the continuous temperature rise of the last 40 years of the 20th century apparent both at Basel and at Saentis. Fig. 2b shows the anomaly of the minimum temperature variance for each year. Unlike the clear increasing trend seen in the temperature records, the variance anomaly for both sites is seen to be essentially close to zero and has been decreasing in an oscillatory manner since the 1940s. Whatever the period considered (e.g., the first 40 years of the century through to the mid-century maximum, the last 20 years when temperature anomalies are systematically positive, or the entire 104-year record), the variance decreases with increasing temperature.

The same conclusions can be reached for the anomalies of maximum temperature (Tmax) means and anomalies for the two sites. Fig. 3a plots the means for Basel and Saentis, the latter site exhibiting a much stronger rise in maximum temperatures than Basel (over 2.3 °C per century compared to 1 °C in Basel), that can be explained by mild winters over the past 20 years in the Alps and associated amplification factors such as increased latent heat warming resulting from a reduction in the duration of snow on the ground, and a reduction of cloudiness at height leading to greater solar irradiance.

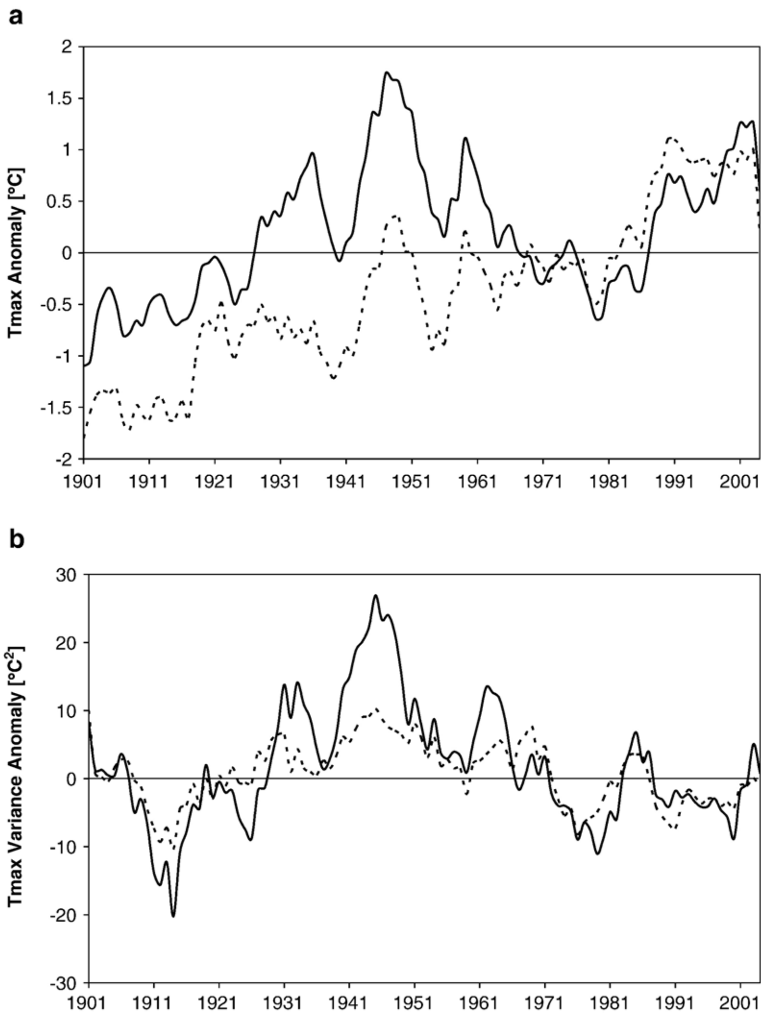

Fig. 3. As Fig. 2, except for maximum temperature anomalies.

At Basel, on the other hand, low-level cloudiness and wintertime temperature inversions have served to modulate the annual average daily maxima to such an extent that the overall increase is smaller than at high elevations. Indeed, the 1940s represent the warmest decade of the record and even taking into account the 2003 heat wave, the anomalies of the last decade are still below those of the 1940s in Basel. For Saentis, positive temperature anomalies were reached in the 1940s for the first time, but then reverted to negative values until they became systematically positive in the early 1980s and peaked in the early 1990s, remaining essentially at their high levels since then. Fig. 3b shows that for both series, the variance anomaly of maximum temperatures are well in phase; the anomalies attain a peak in the mid 1940s and, as for the Tmin variances, have decreased in a series of oscillations to reach values close to zero since the early 1990s at a time when minimum and maximum temperatures were entering into the warmest part of the record not only of the 20th century but probably for much of the past millennium as well (Mann et al., 1999; Pfister et al., 1999). A simple regression analysis shows either no linear trends ($R^2=0.002$ for Basel) or a slightly negative trend for variance with increasing temperature ($R^2=0.810$ for Saentis) at the 95% statistical significance level.

These two sets of figures have shown that for the Alpine region (data from other Swiss climatological sites confirm these conclusions) there is clearly no direct link between increasing minimum and maximum temperatures and an increase in the variance. Before attempting to provide an explanation for these conclusions that seem contrary to what has been speculated upon for some years, an assessment of the behavior of temperature extremes since 1900 and their relation of to climate variability will be discussed next.

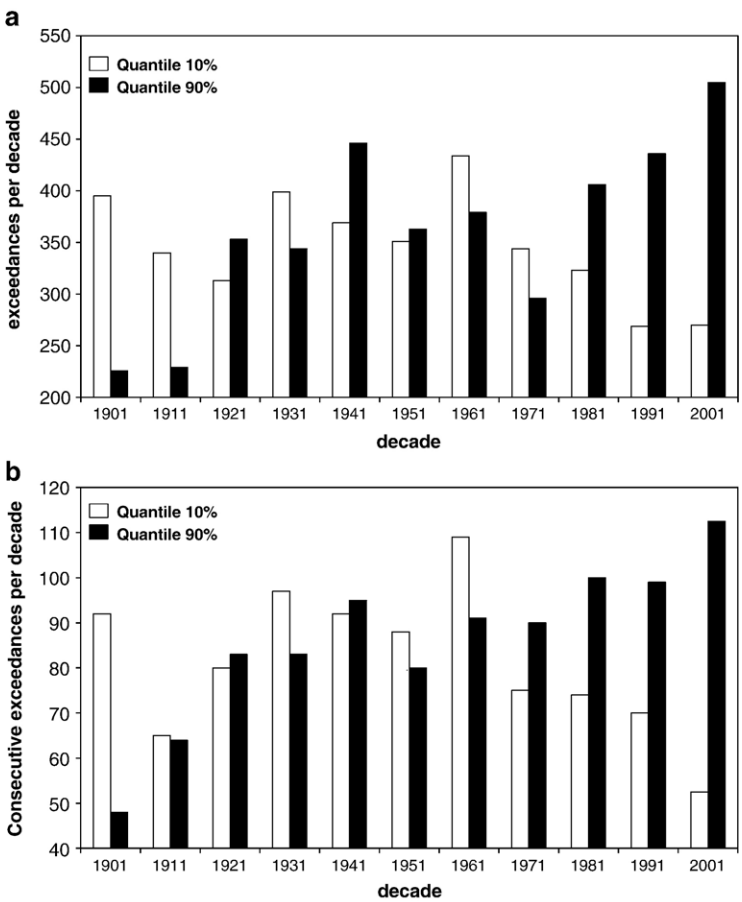

Fig. 4. Decadal changes in the frequency of exceedance (a) of the 10% quantile of minimum temperatures (white histograms; i.e., cold spells) and the 90% quantile of maximum temperatures (black histograms; i.e., warm spells) at Saentis, and the persistence (maximum number of consecutive days) of the 10% and 90% quantiles of minimum and maximum temperatures, respectively (b). The quantile thresholds are computed for the 1961–1990 reference period.

In order to quantify in an objective manner changes in temperature extremes, these have been defined in terms of their 10% and 90% quantiles (hereafter referred to as Q10 and Q90, respectively), based on daily data for the 1961–1990 reference period. The exceedances of minimum temperatures below the 10% quantile threshold and those of temperature maxima above the 90% threshold have then been plotted as a function of time, and the series thus obtained can be viewed as a measure of the persistence of a cold or warm extreme event. Fig. 4 shows the total exceedances above for Saentis on a decade-by-decade basis for Tmin Q10 and Tmax Q90; for the final decade beginning 2001, the data has been linearly extrapolated to 2010 based on the 2001–2004 data and of course needs to be viewed with caution. Fig. 4a shows the total number of exceedances for each decade, while Fig. 4b shows the longest consecutive number of days per decade during which the respective thresholds are exceeded. The persistence of cold events (Tmin Q10) in Fig. 4a ranges from 300 to 400 events in the first 6 decades, peaking at more than 430 events in the 1970s, then drops to less than 270 events in the 1990s and is estimated to remain at these low levels in the first decade of the 21st century. Tmax Q90, on the other hand, is seen to increase by over 30% since the 1970s, and exceeds the mid-century maximum of the 1940s in the past 10 years. For the number of *consecutive days* with Q10 and Q90 exceedances summed for each decade, Fig. 4b allows to reach essentially the same conclusion, i.e., exceedances of Q10 have never been so low in the 20th century as they appear in the 1990s, and Q90 exceedances have never been as high as in the last decade. The link to warmer Tmin and Tmax seems straightforward, and correlations between Tmin Q10 exceedances and mean Tmin attain −0.80 (−0.64 for consecutive days of exceedance), and the corresponding correlation between Tmax Q90 and mean Tmax is 0.87 (0.92 for consecutive days of exceedance). This simply states the obvious conclusion that, as temperatures warm, the occurrences of Tmin extremes diminish and those of Tmax increase.

There are no significant links between the exceedances of Tmin Q10 or Tmax Q90 with the variability of climate expressed in terms of the variance of Tmin and Tmax, respectively. As in the preceding analysis involving temperature anomalies and their respective variances, there is no clear relationship between the marked changes in the persistence of cold and warm extremes and the variability of climate. In particular, the observed more frequent and persistent exceedances of the upper tail of the Tmax PDF in the latter part of the 20th century does not lead to a rise in the variance of the distribution as could be expected, perhaps because the change in mean temperature is accompanied by a symmetrical shift in the temperature PDF, as illustrated in Fig. 1a.

These somewhat surprising results, whereby a general reduction in variance occurs at a time when mean minimum and maximum temperatures are increasing substantially, and extremes in the warm tails of the temperature PDFs are becoming more frequent, can be partially attributed to changes in weather regimes that have affected the Alpine region over the past century. While there are numerous weather classification systems that characterize weather patterns over Europe (e.g., the Hess–Brezowsky "Grosswetterlagen", Hess and Brezowsky, 1977; the Schuepp classification over the Alps and Central Europe, Schuepp, 1968; etc.), for the sake of clarity a simple four-mode scheme will be discussed here, namely cold–dry and cold–moist winter regimes and warm–dry and warm–moist summer modes. Each "weather type" is defined as a joint exceedance of combinations of Tmin, Tmax, and relative humidity 25% and 75% quantiles whose persistence can be assessed on the basis of the simple threshold criteria provided in Table 1.

Fig. 5 shows the evolution of the four modes defined in Table 1 for Saentis. The cold–dry regime has not changed very substantially since the decade of the 1930s, with persistence of this weather type roughly between 150 and 200 days per decade. The cold–moist mode has, however, undergone the most dramatic change, basically collapsing since the end of the 1970s; it exceeded 500 occurrences per decade up to the 1960s down to 10 in the 1990s; this mode appears very sensitive to high temperatures, as in the 1940s "mid-century optimum", where a sharp reduction is observed prior to a subsequent increase into the 1960s. The warm–dry summer mode has increased since the 1960s and is currently, of the four modes discussed here the most dominant one, although the frequency of exceedance of the joint thresholds is lower at the end of the record than it was in the 1930s and 1940s. The

Table 1
Definition of the cold–dry, cold–moist, warm–dry, and warm–moist modes used in this study. These modes are defined as *joint* exceedances of temperature and moisture thresholds according to the 4 sets of combinations; Q refers to the 25% or 75% quantiles of temperature and relative humidity

Weather regime	Cold+dry	Cold+moist	Warm+dry	Warm+moist
Criteria	Tmin<Q25 RH<Q25	Tmin<Q25 RH>Q75	Tmax>Q75 RH<Q25	Tmax>Q75 RH>Q75

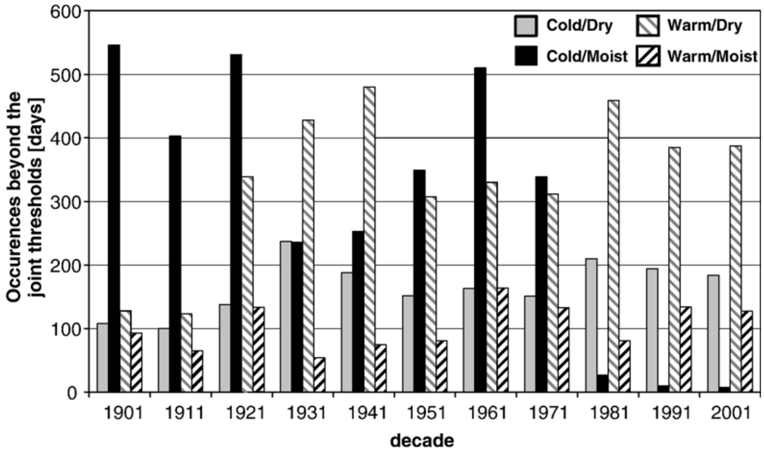

Fig. 5. Decadal changes in the frequency of occurrence of the four weather modes defined in Table 1.

warm–moist mode remains low throughout most of the century at about 100 occurrences per decade, indicative of a tendency for the warmer periods of summers to be associated with dry conditions. In Fig. 5, the data for 2001–2004 has been included and extrapolated linearly to 2010 in order to establish a very approximate trend into the future and to compare the early part of the 21st century with previous decades of the 20th century. This extrapolation should be viewed with caution, however, as extreme events or shifts in circulation patterns could occur during the second half of the decade 2001–2010 and modify the results.

The strong changes in two of the four regimes (decline of the cold–moist mode and dominance of the warm–dry mode) in the last 30 years of the 20th century is related to changing pressure patterns, associated in part to the behavior of the North Atlantic Oscillation (Beniston and Jungo, 2002; Hurrell, 1995; Wanner et al., 2001).

A complementary method to investigate the evolution of weather patterns is through the change of pressure systems recorded at various stations. A statistical analysis of the frequency, the intensity and the persistence of pressure systems above or below particular thresholds gives some indication of the increase of minimum and maximum temperatures and the decrease in their variability during the last decade of the 20th century. Fig. 6a shows the decadal averages of the daily surface pressure anomalies (p_{sfc}) at Basel and Saentis, relative to the 1961–1990 averages. Before 1980, the anomalies were negative on average except during the warmer periods of the 1940s. During the last 20 years of the 20th century, the anomalies are clearly positive reaching more than 1 hPa at Saentis. Fig. 6b shows the standard deviation of these anomalies for both stations over the same period. There are decadal oscillations in these series but variability clearly decreases during the past two decades, particularly at Saentis where the reduction in variability is substantial. In other words, during the last two decades, a larger number of weather systems associated with higher surface pressure have been recorded at both stations. It is hypothesised that these systems would influence the long term variability diagnosed earlier in the observed series of Tmin and Tmax through their persistence. In order to analyse the frequency of exceedance of high pressure occurrences at Saentis and Basel, Fig. 7a illustrates the total exceedances below the 10% quantile pressure threshold and Fig. 7b for those above the 90% threshold plotted for each decade of the 20th century. The frequencies of low pressure systems exhibit similar decadal variation at both stations, ranging from 240 to 450 events. A relative minimum of persistence is seen during the 1940s, peaking during the 1960s, and decreasing steadily thereafter. The frequencies of high pressure systems display a contrary behavior with a range from 280 to 490 events. A relative maximum of high pressure is seen during the 1940s, followed by minimum occurrences during the 1960s, subsequently increasing to more than 450 events during the 1990s. At both stations, there has been a positive shift in the surface pressure distribution between the first and the last decade of the 20th century. Interestingly enough, the surface pressure minima have undergone a slight increase whereas the surface pressure maxima have not changed significantly over the decades. Consequently the kurtosis of the pressure distributions has increased, resulting in more "peaked" distributions at the end of the century. Fig. 8 shows the differences between the exceedance distributions for the beginning

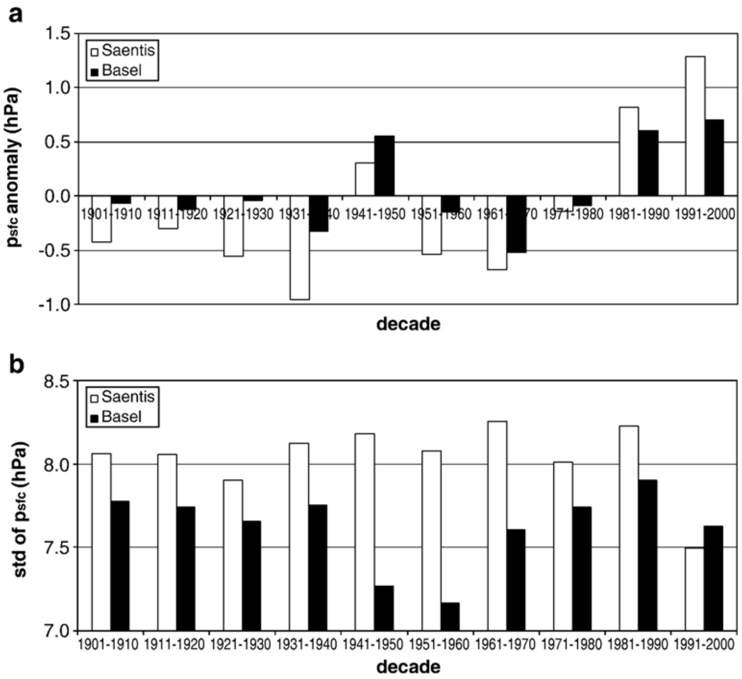

Fig. 6. Decadal variation of surface pressure anomalies at Basel and Saentis based on the 1961–1990 average (a) and of the variation of the standard deviation (b) at both stations.

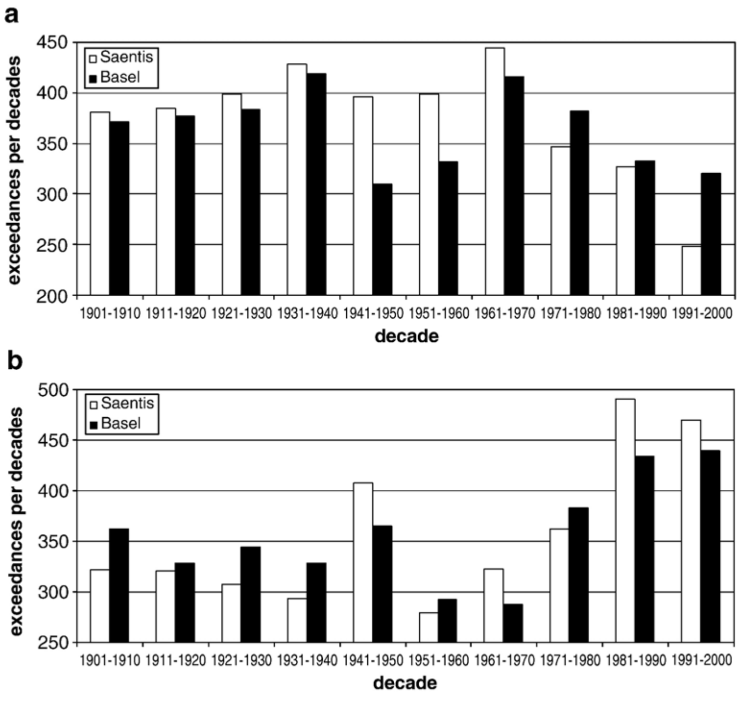

Fig. 7. Decadal changes in the frequency of exceedance (a) of the 10% quantile of the surface pressure (low pressure systems) measured at Basel and Saentis and (b) changes in the frequency of exceedance of the 90% quantile of the same quantity (anticyclones) at both stations.

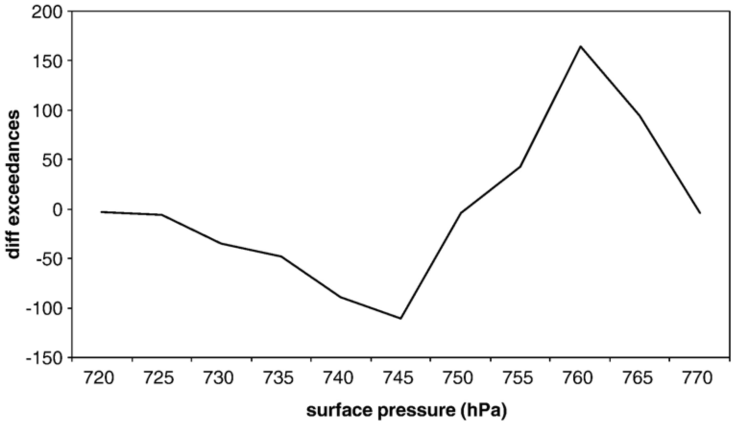

Fig. 8. Change in the frequency of occurrence of the distribution of surface pressure at Saentis, between the decades 1991–2000 and 1901–1910.

and for end of the century, namely the decreased frequency of cyclonic situations and the significant increase in the frequency of anticyclonic situations. This behavior is particularly important from the early 1980s at both stations. In addition, the persistence of anticyclonic situations has generally increased over the decades at both stations. For example, exceedances shown in Fig. 9 for the Saentis are varying from periods of 1–3 days to periods of 11–20 days. The persistence of events lasting 1–3 days increases from the 1960s to the end of the century, from 72 to 112 exceedances per decade. The 4 to 10-day persistence increases slightly whereas the longer persistence, i.e., 11–20 days exhibits a decrease throughout the course of the century, but these are relatively rare events; the decadal persistence summed over all the periods returns the frequency of exceedances. Consequently, the strong anticyclonic situations are generally more frequent and persistent at the end of the 20th century than at the beginning at both Swiss stations.

The question therefore arises as to how these high pressure systems influence the increase of daily temperature extremes and the decrease of their variability. When analysing some of the longer term, or more persistent, high pressure systems recorded at both stations, one may conclude that these situations are associated with blocking highs; a careful analysis of the weather patterns giving rise to these will help to draw more formal conclusions but this issue is well beyond the scope of this paper. Indeed, the weather in a blocking high as well as its eastern and western peripheries remains rather uniform. Among the longest persistence recorded at Saentis, one finds the summers of 1969, 1975 and 1976 with 17, 9 and 13-day blocking high pressure systems, respectively, as well as the blocking episode that resulted in the 2003 heat wave in Europe (Beniston and Diaz, 2004). Blocking high episodes also occur during winters, frequently leading to large departures from the mean (e.g., more than 16 °C anomaly in February 1998, as reported by Beniston, 2005).

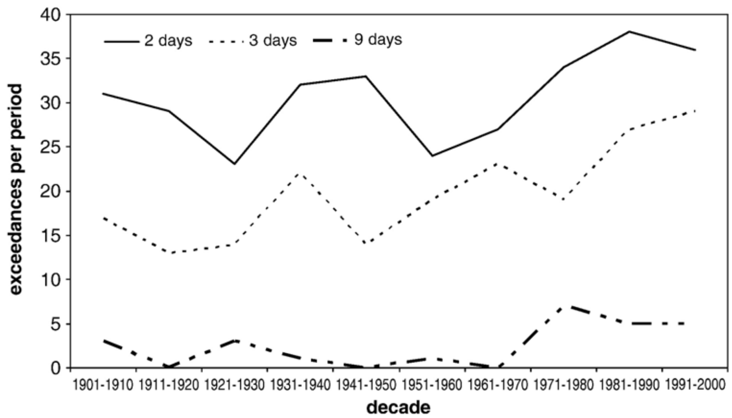

Fig. 9. Change in the persistence of anticyclonic situation (p_{sfc} > 90% quantile) at Saentis: the persistence is plotted for 2-day, 3-day and 9-day periods.

Table 2a displays the variability of the *daily* temperature extremes at both Basel and Saentis measured as the standard deviation that ranges from 6.6 °C to 8.8 °C over the period 1901–2000. The analysis of variability reveals, however, that the standard deviations are systematically lower for anticyclonic situations (Table 2b), i.e., when the surface pressure exceeds the 90% quantile; the difference is 1.5 °C on average at both stations. Consequently, more frequent and more persistent anticyclonic situations induce a reduction in the variability of temperature extremes.

The surface pressure values recorded during the warm–dry mode depicted in the previous section is qualified as relatively high since 95% of the cases lie above the 90% quantile.

Madden and Sadeh (1975) have shown that the evidence of changes in the statistical properties of surface pressure (means and standard deviation) at Zürich is small for the period 1901–1949. Similar conclusions can be reached with the daily-average pressure shown in this paper for the Basel and Saentis stations during the same period. However, emphasis is placed on the fact that a significant change occurred after 1970 for the studied variables (Tmin, Tmax) and these may be explained by the change in the persistence of the daily pressure data. The present analyses consider the period 1961–1990 to be the late 20th century climatic norm; however, the same conclusions can also be drawn if the entire period from 1901–2004 is used as the reference period or comparison purposes. In their discussion, Madden and Sadeh (1975) state that by considering the pressure time series at Zurich from 1901–1949, the persistent character of station pressure is less in summer than in winter. If the characteristic time between truly independent sample values is roughly of 5 days in summer and 12 days in winter prove to be typical of atmospheric variables, then a given relative standard error for time averages could be reached in only slightly more than half the averaging time for the summer hemisphere than for the winter hemisphere. The observed records show that the longest persistence of all the studied variables are greater than these characteristic times between independent samples; the phenomena studied here are thus not purely an artefact of an autocorrelation process and but more the sign that there is a genuine decrease in the climatic variability of surface temperature and pressures.

Table 2a
Standard deviations of Tmin and Tmax at both Saentis and Basel stations for the period 1901–2000

Standard deviation for	Saentis		Basel	
	Tmin	Tmax	Tmin	Tmax
1901–2000	6.7 °C	6.9 °C	6.6 °C	8.8 °C

Table 2b
Standard deviations of Tmin and Tmax at both Saentis and Basel stations for cases for which the surface pressure is either greater than or lower than the 90% quantile

Standard deviation for	Saentis	Basel
$T_{max}\,\vert p_{sfc}>90\%$ quantile	5.0 °C	6.9 °C
$T_{max}\vert p_{sfc}<90\%$ quantile	6.5 °C	8.7 °C
$T_{min}\vert p_{sfc}>90\%$ quantile	4.7 °C	5.3 °C
$T_{min}\vert p_{sfc}<90\%$ quantile	6.4 °C	6.4 °C

4. Modeling current and future changes in extremes

In order to investigate possible changes in variance and persistence based on results of the HIRHAM4 model simulations for a future climate forced by increased atmospheric greenhouse gases as suggested by the IPCC A-2 scenario discussed in Section 2, it is first necessary to assess that model's capacity in reproducing the observed situation.

Table 3 provides an overview of some of the statistics related to Tmin and Tmax at Basel and Saentis, for the observed 1961–1990 period, the same period as simulated by the HIRHAM RCM, and the 2071–2100 time window for a climate in which the A-2 scenario is assumed. With the exception of Tmin at Basel, the simulations of mean Tmin and Tmax at both locations are in reasonably good agreement to within ±1 °C; the model systematically overestimates temperatures, and particularly so for Basel, where the model exhibits a warm bias of close to 3 °C. This is possibly due to the fact that the model does not reproduce well wintertime inversion conditions at low elevations in this region that considerably modulate Tmin values beneath the inversion layer. Variances are in close agreement between observations and the RCM for Tmin, but a little less so for Tmax, where variances are over or underestimated by up to 16.0 °C^2 (corresponding to a standard deviation difference in the worst case of about 1 °C, which remains acceptable). The inter-quantile range (IQR), i.e., the difference between the 90% and 10% quantiles in Table 3, as a measure of substantially-different shapes of the probability density functions (PDF) of Tmin and Tmax at both Basel and Saentis are remarkably similar in both the observations and the simulations, and indeed are fairly similar for Tmin and Tmax at both sites. In addition to the warm bias in the model, small changes in shape help explain the differences between the 10% and 90% quantiles of the observed and simulated

Table 3
Comparison between observed statistics and model data for the 1961–1990 period at Basel and Saentis for minimum (Tmin) and maximum (Tmax) temperatures, respectively, and shifts in these statistics in a changing climate under the IPCC A-2 Scenario

	Obs. 1961–1990	Model 1961–1990	Model 2071–2100
Basel Tmin			
Mean (°C)	5.7	8.6	12.3
Variance (°C^2)	41.7	45.5	46.7
10% quantile (Q10; °C)	−2.2	0.0	4.1
90% quantile (Q90; °C)	14.0	17.3	21.6
Exceedance below −5 °C (days/decade)	169	106	12
Longest persistence below −5 °C (days)	28	19	7
Basel Tmax			
Mean (°C)	14.5	15.0	19.0
Variance (°C^2)	76.2	60.4	76.7
10% quantile (Q10; °C)	2.7	4.5	8.6
90% quantile (Q90; °C)	25.8	25.6	31.3
Exceedance above 30 °C (days/decade)	83	59	434
Longest persistence above 30 °C (days)	13	9	46
Saentis Tmin			
Mean (°C)	−4.2	−3.8	0.0
Variance (°C^2)	45.7	49.2	47.1
10% quantile (Q10; °C)	−13.3	−12.7	−8.4
90% quantile (Q90; °C)	4.5	5.1	9.1
Exceedance below −15 °C (days/decade)	218	222	54
Longest persistence below −15 °C (days)	16	16	9
Saentis Tmax			
Mean (°C)	1.0	1.8	5.8
Variance (°C^2)	46.7	59.6	73.4
10% quantile (Q10; °C)	−7.8	−8.3	−4.7
90% quantile (Q90; °C)	10.1	12.4	17.7
Exceedance above 20 °C (days/decade)	3	12	195
Longest persistence above 20 °C (days)	8	8	22

distributions, since even a minor difference in the skewness and kurtosis of the distribution can lead to discrepancies between the observed and simulated quantiles; these differences nevertheless remain within 2–3 °C. The same argument can be used to explain the differences in exceedances beyond the selected thresholds (−5 °C and+30 °C for Basel, and −15 °C and+20 °C for Saentis), since the shape of the PDF and its tails are determining factors for exceedances. The exceedances of the selected thresholds are nonetheless fairly well reproduced by the model, albeit with an underestimation of the number of days in Basel where Tmin is inferior to −5 °C and an overestimation of the number of days per decade where Tmax is above 20 °C threshold at Saentis. The maximum persistence of events below or above the selected thresholds is also in reasonable accord with the observations; this is just one measure of persistence and does not include, for example, the recurrence of persistent events beyond the given thresholds in a single year.

Despite some clear differences in some of the model statistics compared to observations, particularly total exceedances, the HIRHAM model results remain within reasonable bounds of error and enable some measure of change under enhanced greenhouse-gas concentrations for the period 2071–2100. The rightmost column of Table 3 features the RCM-generated statistics for the future climate scenario at Basel and Saentis. The high emissions A-2 scenario leads to a wintertime and summertime increase of Tmin and Tmax of about 4 °C as already shown by Beniston (2004) at both locations. According to this particular model realization, the variance of Tmin does not change to any extent, implying a general shift of the temperature PDF towards warmer temperatures; the tails of the distribution change by the same amount as the change in mean. For Tmax, on the other hand, the HIRHAM model suggests that the variance will increase, as seen in Table 3, thereby implying that a disproportionate shift in the upper tails of the maximum temperature PDF can be expected to occur compared to the change in mean conditions (see Fig. 1b). This is evidenced by the 10% and 90% quantiles, whereby the shift in the lower and upper tails of the Tmin PDF is about 4 °C (i.e., identical to the rise in mean Tmin between the 2071–2100 and the 1961–1990 periods), whereas for Tmax, while the 10% quantile increases by 4 °C, the 90% quantile increases by 5 °C at Saentis and even 6 °C at Basel, suggesting a widening of the Tmax PDF and thus an increase in the variance.

The exceedance of Tmin and Tmax beyond the selected thresholds changes dramatically between the reference 1961–1990 time frame and the 2071–2100 scenario; the number of “cold days” as specified by the respective thresholds at Basel and Saentis sharply diminishes between the two 30-year time windows, while the number of “warm days” is seen to increase very substantially. Even taking into account the error margin of the model results, the changes between current and future climates are so large that they are highly significant. It is interesting to note that while the longest number of consecutive days beyond the given threshold decreases for Tmin at both locations, the persistence of events beyond the Tmax threshold increases considerably.

The HIRHAM model results thus suggest a rather paradoxical change in the behavior of minimum and maximum temperatures, namely little change in the variance of Tmin and Tmax, i.e., an increase in *both* the variance of the Tmax PDF *and* the maximum persistence of events beyond a given threshold, and a decrease in the maximum persistence of Tmin below a given threshold with little change in the variance.

In other words, the RCM results suggest that diurnal temperatures are likely to be more volatile in the future, with strong persistence of elevated temperatures in summer, while nocturnal temperatures are simulated to be less variable than under current climate, but that persistence of cold temperatures in winter will be of shorter duration.

5. Conclusions

This investigation, carried out for a low (Basel) and a high (Saentis) elevation site in Switzerland, has shown that contrary to what is commonly hypothesized climate variability does not necessarily increase as climate warms. Indeed, it has been shown that the variance of temperature has actually decreased in Switzerland since the 1960s and 1970s at a time when mean temperatures have risen considerably. Nevertheless, these findings are consistent with the temperature analysis carried out by Michaels et al. (1998) where their results also do not support the hypothesis that temperatures have become more variable as global temperatures have increased during the 20th century. The principal reason for this reduction in variability is related to the strong increase in the persistence of certain weather patterns at the expense of other types. A simple weather classification scheme has been designed to highlight this point, based on combinations of warm, cold, moist or dry regimes; according to this classification, winter regimes (cold and moist) associated with perturbed synoptic systems have been sharply reduced in the last decades of the 20th century, while warm and dry summer regimes have become the most persistent since the 1970s. In other words, synoptic weather patterns that are associated with high variability are today less frequent than those patterns associated with high persistence, i.e., low variability. Closer investigation of the behavior of surface pressure fields has highlighted the fact that positive pressure anomalies have increased since the 1970s, and that these are well correlated with the exceedances of temperature at both the low and high elevations.

Simulations of European climate by the HIRHAM regional climate model have shown that the model is capable of reproducing satisfactorily the statistics of variability and persistence of temperature at the two locations, despite a warm bias in the model. The model performance lends credence to the simulations of variability and persistence in a scenario climate for a time window from 2071–2100. For the Swiss sites, the scenario simulations suggest an average increase of approximately 4 °C for both minimum and maximum temperatures, but the behavior of variability and persistence is different between minimum and maximum temperatures. The variance of temperature minima changes little in the future compared to current (1961–1990) climate, while the maxima exhibit an increase in both variance and persistence. Because of the strong warming that the IPCC A-2 scenario implies, exceedances below and above selected temperature thresholds change dramatically; cold events still occur in the future, but become rare compared to today, while warm events become much more common. For example, the number of occurrences of 30 °C or more increases 5-fold in Basel compared to today, from about 80 events per decade currently (60 according to the HIRHAM simulations) to over 430 event per decade by 2100, with the longest persistence of the number of consecutive days above 30 °C increasing from about 10 days currently to close to 50 days in the scenario climate.

The changes in exceedances between future and current climate are, at least for Switzerland, to a large degree associated with a change in mean temperatures and to a lesser extent to an increase in the variance of maximum temperatures. Here, the broadening of the temperature probability density function enhances the exceedance and persistence of warm events for the upper tail of the distribution; this is also reflected in the value of the 90% quantile of maximum temperature that increases by over 5 °C for an average temperature increase of 4 °C from 1961–1990 to 2071–2100.

The change in the variability and in the persistence of maximum temperatures, resulting in long, very warm periods in the future, will certainly have an impact on many sectors, such as human health (increase in heat-related morbidity and mortality), ecosystems and agriculture (particularly during heat-waves that are also accompanied by drought) and water quantity and quality. In winter, the rise in average minimum temperatures and the reduction of cold spells will have a strong influence on the behavior of the Alpine snow pack. Changes in the snow pack height and duration will in turn have a determining influence on the seasonality and amount of discharge in rivers originating in the Alps, as well as on the timing of the start of the vegetation cycle for many plant species. Studies such as this should prompt decision makers to consider appropriate adaptation strategies to help reduce the likely impacts of the changes in climate variability and persistence that have been discussed here.

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