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Decadal-scale changes in the tails of probability distribution functions of climate variables in Switzerland

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ABSTRACT: An analysis of several Swiss climatological sites reveals that a substantial change in the behaviour of pressure, minimum and maximum temperature extremes has occurred in the past two decades. Extreme cold tails defined by the 10% quantiles of temperature drop by a factor of 2 or 3, while the upper tails (beyond the 90% quantile) exhibit a four- or five-fold increase in all seasons. Pressure shows contrasting behaviour, with increases in wintertime highs and summertime lows, while precipitation shows little change. On the basis of the observed datasets, temperature biases related to extremes of pressure or precipitation have been computed, as well as for joint combinations of precipitation and pressure extremes. The most dominant bias is associated with periods without rainfall, during which temperatures are at least 1 °C warmer than otherwise. Changes in the behaviour of joint combinations of extreme pressure and precipitation regimes also have a discernible influence on temperatures. Copyright © 2008 Royal Meteorological Society

KEY WORDS climatic change; extremes; probability density functions

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1. Introduction

Much of the recent work dealing with the statistics of extremes has focused on the behaviour of the tails of the probability density function (PDF) of a particular climate variable, which provides one objective measure of an extreme. The 10 and 90% quantiles as suggested *inter alia* by the IPCC (2001) are the most commonly used thresholds to define extremes. There have been many investigations that have highlighted possible relations between changes in mean climate and shifts in the extremes of a particular variable (e.g. Mearns *et al*., 1984; Frich *et al*., 2002; Klein Tank and Können, 2003). Studies relating a number of different forms of extremes to climate patterns as defined for example by principle component analysis (PCA) have also been conducted, in order to assess which modes of climate exert an influence on the frequency and/or the intensity of extremes (e.g. von Storch and Zwiers, 1999). These studies have yielded mixed results, because however we look at extremes, it is difficult to relate rare and/or intense events to long-term changes in mean climate.

The objectives of this paper are two-fold: firstly, to report on decadal-scale changes of quantiles of temperature, pressure and moisture for Swiss climatological sites that have long and homogeneous time series; and secondly, to assess the behaviour of temperatures during the periods in which precipitation and pressure are within their extreme modes.

The paper will revisit a concept discussed by Beniston and Goyette (2007) that uses *joint* PDFs (e.g. of pressure and precipitation) as a measure of changes in weather patterns that may influence temperature. Numerous weather classification systems characterizing weather patterns over Europe that can be used to relate changes in mean and extreme climates (e.g. the 'Grosswetterlagen' by Hess and Bresowski, 1977; or the Schuepp classification for the Alps, Schuepp, 1968), but the simpler scheme defined by Beniston and Goyette (2007) allows an assessment not only of the extremes of a single variable, where similar behaviour could have different underlying causes, but also of combinations of variables (e.g. dry/high-pressure or moist/low-pressure conditions) that reflect particular modes of atmospheric circulation.

2. Data and methods

The data employed in the present paper stem from the digital climatological database of the Swiss weather service, MeteoSwiss. This investigation has compiled data from both low (Basel, 369 m asl; Neuchâtel, 487 m; and Zurich, 569 m) and high-elevation sites (Engelberg, 1018 m; Davos, 1590 m; and Saentis, 2500 m); the location of these stations is shown in the map provided in Figure 1. It is often interesting to distinguish low and high elevations, because the latter are closer to free atmospheric conditions and less subject to contamination by low-level boundary-layer influences, wintertime thermal inversions, etc. (Beniston and Diaz, 2004). The data sets used have been quality checked by MeteoSwiss in terms

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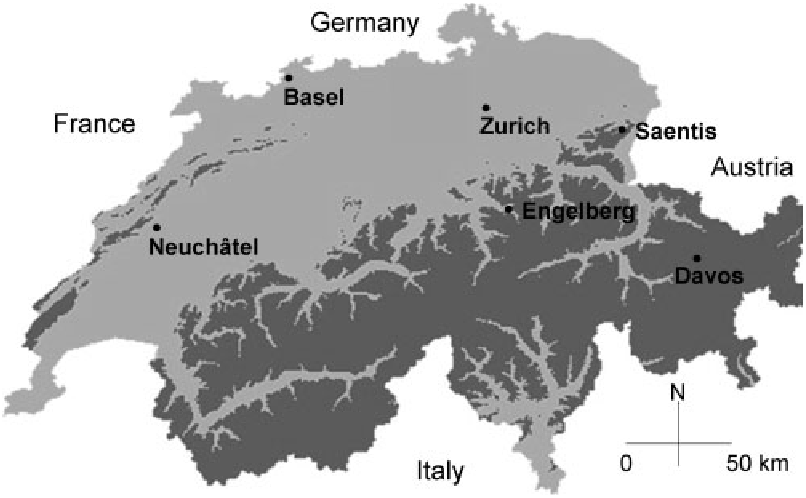

Figure 1. Map of Switzerland showing the six selected sites used in this study. Dark grey shading emphasizes regions where the altitude is greater than 1200 m asl.

of homogeneity in the records and continuity in the geographical location of the measurement stations (Begert *et al*., 2005). As such, Switzerland is an ideal locale for diurnal to century scale climatological time-series analyses, as has been shown in earlier publications (e.g. Beniston and Diaz, 2004; Schaer *et al*., 2004; Beniston, 2005). In the following discussions, sets of daily data are used to compute seasonal means, i.e. according to the commonly used three-monthly periods December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON).

The reference 10 and 90% quantile thresholds are calculated using the daily temperature, precipitation and pressure data for each season for the 30-year reference period 1961–1990, i.e. 30 years × 90, 91 or 92 days, or 2700–2760 data points, according to the season. The thresholds calculated in this manner then serve to define the exceedances for all the time periods considered in this paper and defined in the next section.

The computation of joint tails of the PDFs of two climate variables $V1$ and $V2$ involves a fairly simple procedure whereby simultaneous exceedances of $V1$ and $V2$ for combinations of the 10 and 90% quantiles are computed, i.e. $V1_{10}/V2_{10}$, $V1_{10}/V2_{90}$, $V1_{90}/V2_{10}$, and $V1_{90}/V2_{90}$; subscripts 10 and 90 refer to the respective quantile level for variable $V1$ and $V2$. Frequencies are computed by counting the number of occurrences above or below a particular quantile threshold for each season and each year.

3. Results and discussion

3.1. Changes in quantiles

Most of the results discussed here will focus essentially on the low-elevation Zurich and the high-elevation Saentis sites. The results for the other observing stations are very similar to what is reported here, emphasizing the fact that decadal-scale changes in extremes of pressure and temperature are essentially governed by the same synoptic situations; some comparisons between all stations in addition to the two principal sites will be provided later in this paper to demonstrate this point.

Figure 2 illustrates the winter and summer seasonal changes in the quantile distributions of pressure, minimum and maximum temperature, and precipitation for distinct periods since 1901 at the high-elevation Saentis site. In order to assess whether significant change has taken place over the past century, 20-year blocks have been selected, i.e. 1901–1920, 1931–1950, 1961–1980, and the most recent 20 years of the record from 1988–2007. The term 'significant' refers to any departure of the data points outside the 95% quantile range defined by the reference period 1961–1990. For example, in the graph for winter T_{min} quantile distribution, any value located below six occurrences or above 12 occurrences per season (i.e. the lower and upper bounds of the 95% quantile range) would thus be significantly different from the values located within these limits. Quantile intervals for pressure and temperature are shown by increments of 10%. Because of the very highly skewed nature of the PDF of precipitation intensities, irregular intervals have been selected: less than the 50% quantile, then 10% intervals through to the 90% quantile, followed by the range 90–95%, 95–99%, and beyond the 99% quantile.

In terms of wintertime quantiles, pressure and temperature exhibit very similar behaviour, with relatively uniform exceedances for each quantile interval that tail off towards the higher quantiles for the first three sets of 20-year blocks, i.e. through to the end of the 1970s. The most recent 20-year period, on the other hand, exhibits a totally different behaviour, with a reduction in the number of exceedances of the lowest quantile range (0–10%) by a factor of two and a sharp rise in the exceedances beyond the 90% quantile. In this upper part of the PDF, very high pressure increases from 5 events per winter in earlier times to 18 events per winter for the most recent 20-year period; for minimum temperatures, the shift is from 6 to

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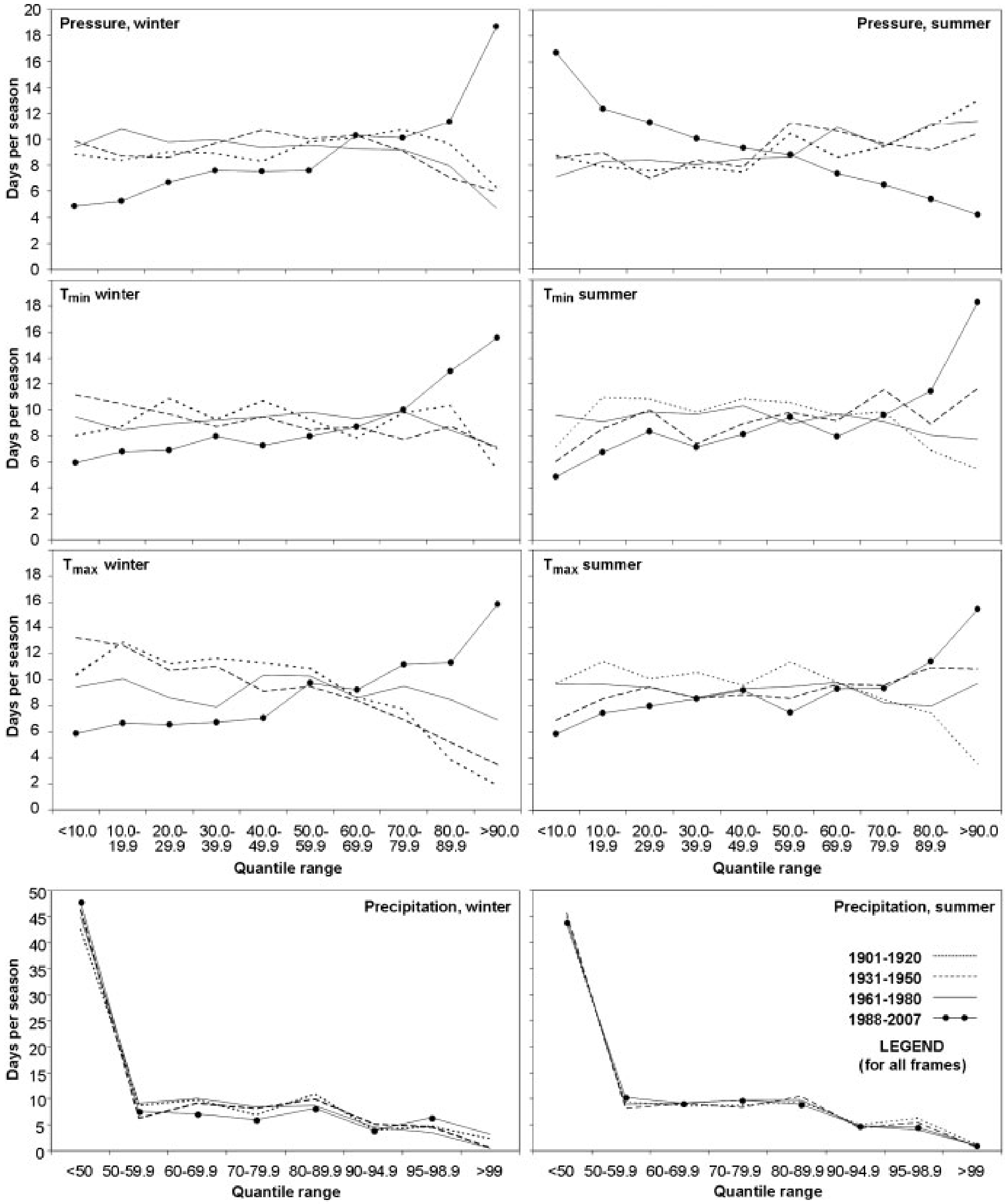

Figure 2. Changes in the behaviour of pressure, minimum and maximum temperatures and precipitation for winter (left) and summer (right) at Saentis (2500 m asl), for selected quantile intervals. The ordinate gives the number of occurrences per season.

16 events per season, and 2 to 16 events (i.e. an eight-fold increase) for maximum temperatures. The change is not progressive throughout the twentieth century but is particularly abrupt in the latter part of the record; the quantile distribution for the 1961–1980 period resembles far more the earlier 1901–1920 and 1931–1950 blocks than the 1988–2007 profile, suggesting that a major and rapid change in the behaviour of the tails of the distribution has taken place in the most recent period.

Summertime quantile distributions also exhibit the major shifts in the tails of the distribution. For example, the exceedances of the low tail of pressure increase by a factor of two while those at the upper tail decrease by a factor of 3. Summertime low pressure is thus more frequent in the recent part of the record than high pressure, reversing the situation that prevailed prior to the 1980s. Exceedances of minimum and maximum temperatures across the quantile range, however, show the same tendencies to change as their wintertime counterparts, with a 2–3 times increase beyond the 90% quantile and around 50% reduction in the exceedances below the 10% quantile.

The exceedances of precipitation beyond the selected thresholds defined above show no significant changes in any part of the quantile range, and no seasonal change either. There is a large clustering below the 50% quantile (i.e. in the range 0–0.5 mm/day), a rapid decrease to less than 5 days per season in the 90–95% quantile range and 1 day or less for the 99% threshold.

The statistics for the other stations assessed in this study are all in line with what has been reported here, with the possible exception of the summer threshold exceedances of maximum temperatures at the low-elevation sites of Basel and Zurich. At these sites, the exceedances of the upper quantile range were greater in the 1931–1950 period than the most recent part of the record. This is because in the lower parts of the country, the clustering of very warm summers in the 1940s and into the early 1950s led to exceedances of temperatures even larger than those associated with some of the warm summers such as 1994, 2003 and 2006. The distribution across the quantile range for 1931–1950 and 1988–2007 are thus very similar in Basel and Zurich and are not as clearly separated as in the case of the higher elevations (Engelberg, Davos and Saentis).

Changes in the exceedances of joint quantiles of precipitation and pressure serve to highlight changes in the behaviour of the following extreme weather combinations, themselves linked to distinct sets of circulation patterns: low precipitation/low pressure (LL); low precipitation/high pressure (LH); high precipitation/low pressure (HL) and high precipitation/high pressure (HH). Figure 3 illustrates the changes in each set of joint exceedances for Zurich in winter and summer for the four 20-year periods 1901–1920, 1931–1950, 1961–1980 and 1988–2007. The most conspicuous shift is seen to occur in winter with a major jump in the LH combination in the latter part of the record, representing a four-fold increase in the occurrence of this combination compared to earlier periods and totalling on average 15–20 days per winter. The other combinations remain low throughout the record, between 2 and 5 occurrences per season; combinations such as HH have a low frequency of occurrence, which is to be expected since the onset of heavy precipitation under very high pressure conditions would normally be rare. The same tendencies are also observed at the other low and high-elevation sites; Table I shows the change at all six stations between the periods 1901–1920 and 1988–2007 only for the LH mode in order to qualify this statement. The close similarity between the station data suggests that the same synoptic-scale forcing patterns are responsible for the changes in the frequencies of joint quantile modes.

In summer, the most significant change is also related to the high precipitation/low-pressure (HL) combination that exhibits a sharp drop in the latter part of the record from an average of 10–12 events per summer to 3 currently. The other combinations remain low, although the LL and LH modes have increased in the last 20 years. Paradoxically, the increase in summer low-pressure extremes shown in Figure 2 is not accompanied by an increase in heavy precipitation during these events, on the contrary. Even though summertime lows increase substantially, probably as a result of very warm surface

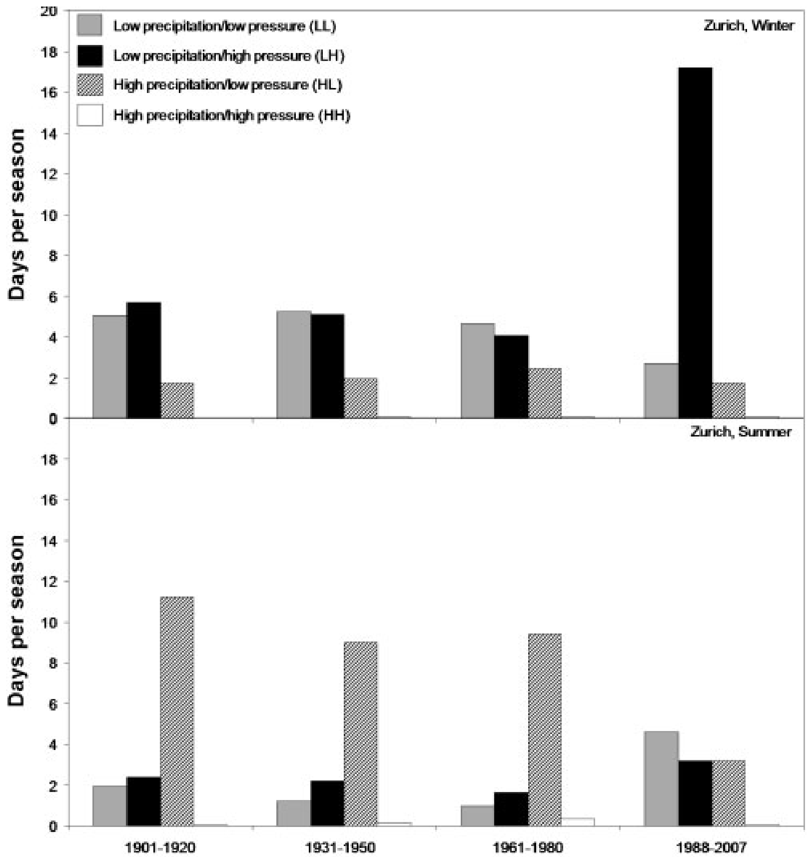

Figure 3. Behaviour of the joint extreme quantile distributions of precipitation and pressure for Zurich in winter (upper) and summer (lower).

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Table I. Comparisons of the number of days during which the LH precipitation/pressure mode (see text for details) occurs at all six observing sites, for the periods 1901–1920 and 1988–2007.

	Basel	Davos	Engelberg	Neuchatel	Saentis	Zurich
1901–1920	6	6	5	7	5	6
1988–2007	18	16	16	18	18	17

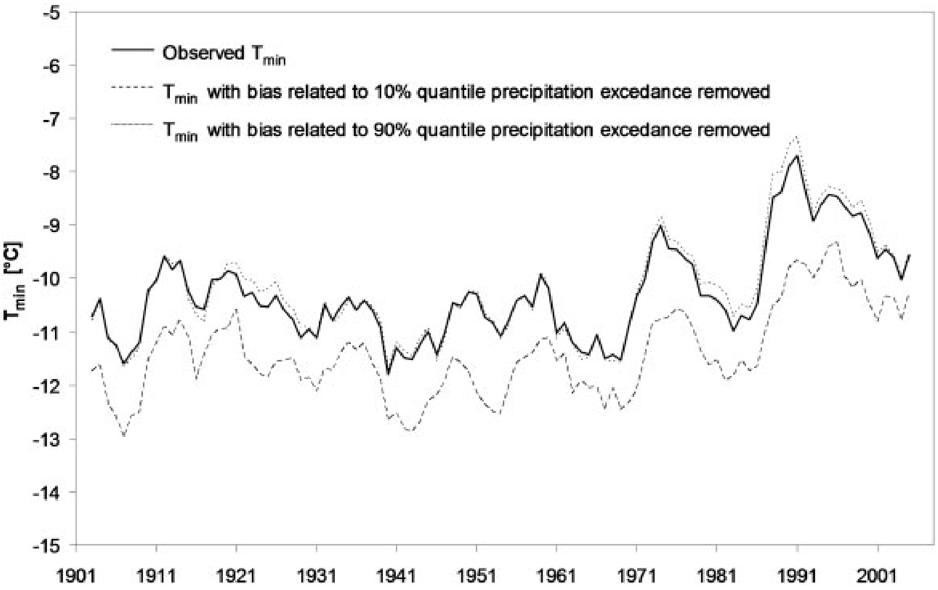

Figure 4. Bias of minimum temperature at Saentis in the presence of precipitation during dry conditions (<0.5 mm/day) or above the 90% quantile.

conditions, they are currently drier than earlier in the record because of reduced moisture convergence into the Alpine region.

3.2. Temperature biases linked to pressure and precipitation extremes

In order to assess the possible relations between temperatures and the low and high tails of pressure and precipitation, and joint combinations thereof, the values of T_{min} and T_{max} have first been averaged for the entire record. As a second step, temperatures observed only during events where the extreme thresholds are exceeded are removed from the record and a new average is computed. This simple arithmetic procedure enables to highlight the temperatures that would have occurred if the extreme thresholds had not been exceeded, thereby quantifying the temperature bias related to the threshold exceedance.

As an example of the behaviour of T_{min} in the presence or absence of extreme values of precipitation or pressure, Figure 4 illustrates the observed T_{min} temperature curve for Saentis, upon which the bias is removed when the 10 and 90% quantiles are exceeded. For precipitation, it is seen that if dry conditions were not as frequent as they are, temperatures would be on average 1.1 °C cooler than observed. In contrast, the bias related to heavy precipitation is minor, barely 0.1 °C warmer than the measured T_{min}. The strong influence of dry days on T_{min} does not serve to explain any part of the general rise of temperatures through the course of the twentieth century, since the bias remains fairly constant throughout, a conclusion that holds for all high and low-elevation sites analysed in this study. Very low pressure is linked to a small positive T_{min} bias in Zurich of less than 0.1 °C, while extreme high pressure, on the other hand, exerts a stronger bias. Temperatures in the absence of the influence of the upper tail of the pressure PDF would be cooler than observed; the most discernible bias in the 1980s and 1990s occurs at a time where the North Atlantic Oscillation was in a persistent, positive phase resulting in anomalously high surface pressure in the Alps that often persisted for several weeks at a time (Beniston and Jungo, 2002). It is in this period that the jump in the frequency of occurrence of very high pressure occurs, as seen in Figure 2. Under such conditions, subsiding air and consequent adiabatic compression results in positive temperature anomalies in the mountains. During the 1980s and 1990s, the temperature bias associated with pressure events beyond the 90% quantile is about 0.4 °C compared to around 0.2 °C prior to the 1980s. While the other mountain sites have a very similar behaviour (pre-1980s bias: 0.18 and 0.15, respectively, for Engelberg and Davos; bias for 1988–2007: 0.35 and 0.42, respectively), observations at low elevations such as Zurich, Neuchatel and Basel exhibit an opposite bias. This is because persistent high-pressure systems in winter in the lowland areas of Switzerland are often accompanied by low-level stratus and fog that strongly limits the amount of incoming solar radiation. Surface temperatures beneath

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Table II. Bias in temperatures according to the four modes of precipitation and extremes as illustrated in Figure 3.

	Low precipitation low pressure	Low precipitation high pressure	High precipitation low pressure	High precipitation high pressure
T_{min} 1901–1920	0.03	0.18	−0.01	0.00
T_{min} 1931–1950	0.06	0.17	−0.01	0.00
T_{min} 1961–1980	0.00	0.13	0.00	−0.01
T_{min} 1988–2007	0.00	0.30	−0.01	0.01
T_{max} 1901–1920	−0.01	0.13	−0.14	−0.02
T_{max} 1931–1950	−0.03	0.00	−0.16	−0.05
T_{max} 1961–1980	−0.02	0.09	−0.09	−0.04
T_{max} 1988–2007	0.11	−0.13	−0.15	−0.06

the stratus thus tend to remain very low for as long as the high-pressure system persists. Summertime biases of T_{max} in the presence of both dry conditions and heavy precipitation (not shown) reflect the tendencies of T_{min} in Figure 4; high and low extremes of pressure are associated with biases that remain within +/−0.2 °C.

Table II shows the bias in wintertime T_{min} at Saentis and summertime T_{max} at Zurich, related to the four extreme modes of precipitation/pressure (LL, LH, HL and HH) as defined earlier. The effect of the sudden jump of wintertime mode LH since the 1980s, seen in Figure 3, is reflected by the increase in the positive T_{min} bias that yields temperatures that are 0.2–0.3 °C warmer than if this mode did not exist (the bias is negative in Zurich because of the wintertime inversion conditions already alluded to). The other three modes have no marked bearing on the behaviour of T_{min}. Summertime biases of T_{max} in Zurich remain within a narrow range (+/−0.15 °C). The most consistent bias is associated with the combination of low pressure and high precipitation, probably related to frontal-type rainfall embedded within warm air masses. Although the number of HL events has actually decreased in recent years, as evidenced by Figure 3, temperature biases associated with this mode remain within a narrow range of +/−0.2 °C. This is perhaps indicative of an intensification of the processes that can occur during the HL type of events.

By far, the greatest bias in minimum and maximum temperatures is related to the periods during which rain is absent. As on average very dry conditions occur more than half the time, whatever the season, it is thus no surprise that the influence of persistent dryness is associated with measurable temperature biases. Periods with no precipitation in summer tend to enhance the positive feedback effects of drier soils, as has been mentioned in recent publications (e.g. Seneviratne *et al.*, 2006) and this effect is observed at all altitudes.

4. Conclusions

This paper has used high quality daily data from several low and high-elevation climatological observing sites in Switzerland to assess changes in extremes of temperature, precipitation and pressure, and the manner in which these changes may be inter-related. The analysis has shown that in the last 20 years, there have been significant shifts in the behaviour of temperature and pressure extremes, as recorded in the tails of the distributions, while precipitation shows little change. Extremes of pressure and precipitation, or a combination of modes, are associated with strong biases in temperatures and their long-term trends despite the fact that these extreme conditions account for only a small fraction of each season. Since the 1980s, the strong shifts in pressure extremes, as well as the low precipitation/high pressure (LH) mode have clearly marked the response of minimum and maximum temperatures at all the low and high-elevation sites investigated.

The objective of this paper has been to report on the observed changes in quantiles of temperature, precipitation and pressure, and not to explore the physical mechanisms that account for these changes. The fact that the marked PDF shifts that have occurred in the past 20 years coincides with the warmest part of the temperature record should not be considered, at this stage of the analysis, as necessarily constituting a direct link with the enhanced greenhouse effect. While this may indeed be one of the underlying causes, there are many other possible explanations that could explain the observations, e.g. changes in circulation patterns; behaviour of the North Atlantic Oscillation; changes in cloudiness and soil moisture characteristics, to name but a few. This type of analysis should ideally be undertaken in many other regions of the globe to assess whether what is reported here is a common feature; the work of Hannachi (2006) on the Central England Temperature record using robust statistics to assess the significance of changes in PDFs over time is one example of such a study. In addition, because of the links between extremes of precipitation and pressure, it would be of interest to assess in a future investigation how these relationships may function in a warming climate. Regional climate model (RCM) projections suggest that the upper quantiles of current climate will become the norm under greenhouse-gas scenario climates (IPCC, 2007). According to many RCMs, summertime precipitation in a scenario climate may diminish by up to 30% or more compared to today (e.g. Beniston *et al.*, 2007), such that the temperature biases linked to more extensive dry periods can be expected to be even greater than today, estimated at roughly 1 °C for each additional 10 days without rain.

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