Theor. Appl. Climatol. 49, 135–159 (1994)

Theoretical
and Applied
Climatology

551.583(494)

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An Analysis of Regional Climate Change in Switzerland

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With 26 Figures

Received April 25, 1994

Summary

An analysis of daily climatological data covering the period from 1901 to 1992 for four locations in Switzerland (Zurich, Lugano, Davos, and Säntis) has been made. The study has highlighted the fact that climate change this century is characterized by increases in minimum temperatures of about 2 K, a more modest increase in maximum temperatures (in some instances a decrease of maxima in the latter part of the record), little trend in the precipitation data, and a general decrease of sunshine duration through to the mid 1980s. The interannual variability is generally large, and filtering of the data to remove high-frequency noise shows that the regional climate undergoes a series of fluctuations of between 8 and 20 years' duration. The temperature change over this century is of greater magnitude than the global temperature changes published in the literature, reflecting an amplification of the global signal in the Alpine region; warming has been most intense in the 1940s, followed by the 1980s; the cooling which intervened from the 1950s to the late 1970s was not sufficient to offset the warming in the middle of the century.

Pressure statistics have been compiled as a means of providing a link between the regional-scale climatological variables and the synoptic, supra-regional scale. These statistics show that pressure also exhibits a number of decadal-scale fluctuations, with the appearance of a new and anomalous behavior in the 1980s; in this decade, pressure reaches annual average values far higher than at other times this century. The pressure field is well correlated with the North Atlantic Oscillation (NAO) Index for distinct periods of the record (1931–1950 and 1971–1990) and is almost decorrelated from the NAO Index for the other decades of the century; this is indicative of transition from one climatic régime to another, dominated by zonal flow when the correlation with the NAO Index is high. In the 1980s, when zonal flow over the North Atlantic is strong, episodes of persistent, anomalously high pressures (blocking highs) are seen to occur over Switzerland, particularly during the winter season. The difference between the zonal and non-zonal régimes is particularly marked between the decade of the 1950s and that of the 1980s.

The impact of this change between the 1950s and the 1980s on a number of climatological variables has been investigated statistically in order to provide an illustration of the manner in which changes in synoptic régimes (i.e., 'climate change') impacts upon climate characteristics on a regional scale. The analysis shows that temperature, precipitation, snow depth, and sunshine duration are indeed sensitive to large-scale influences; not only can yearly mean changes be quantified, but also seasonal and monthly fluctuations.

1. Introduction

While there now seems to be a consensus among the climate research community regarding the reality of global climate change due to the enhanced greenhouse effect (Houghton et al., 1990, 1992), there is as yet no clear indication from observations of a direct link between emissions of greenhouse gases from industry and agriculture and the global warming trend of about 0.5 K observed this century. The average rise in temperature since the middle of the last century remains within the natural range of climate variability, and it is not generally believed that an unequivocal signal of man's pressures on the atmospheric enviornment will be observed before several decades.

One reason for this situation is the sparseness of reliable climatological information, which does not allow for significant statistical treatment of data; in addition, small-amplitude signals on the local or regional scales, such as urban heat island effects, can often contaminate climatological time-series. If a dense network of observing stations is available, however, it should be possible to detect tendencies in such variables as temperature and precipitation, and to infer hypotheses for the observed data which could provide insight into climate change on the regional scale. In addition, observational data are of key importance when attempting some form of downscaling procedure to investigate climate features in a region of interest (Beniston, 1994). It is only through adequate intercomparison with the real world that models of past and present-day climate can be calibrated sufficiently to provide some measure of confidence for future climate simulations. Unfortunately, observational data of the quality required to test and validate model simulations are generally sparse both in time and space. One notable exception is, however, the Swiss Climate Data Base (SCDB), which has been used in this study to analyse the temporal trends of a number of climatological variables in Switzerland.

The SCDB comprises one of the densest climatological networks in the world, with over 150 stations distributed over the Swiss territory (approx. 41,300 km^2). A large number of the climatological stations have continuous daily data in digital form (Bantle, 1989) and six of these have records in digital form stretching back to 1901. Additional records exist which date back to the last century, but these are not available on the computerized database.

The present paper has several objectives:

- to identify changes in climate variables in Switzerland from 1901–1992
- to place these trends within the context of global climate change
- to determine possible causal mechanisms
- to identify the response of regional scale climate parameters to large-scale forcings.

2. Features of Observed Climate in Switzerland, 1901–1992

The climate of the Alpine region is one of considerable interest and complexity, not only because of the physical influence of the Alps on synoptic weather features (gravity waves, wave breaking, blocking situations, etc.), but also because a number of different climatological régimes converge on the region. The complexity of Alpine climates in terms of macro-scale features is brought about by the competing influence of Mediterranean, continental, Atlantic, and Polar régimes. Any response to global climate change will probably result in the altered frequencies of these principal

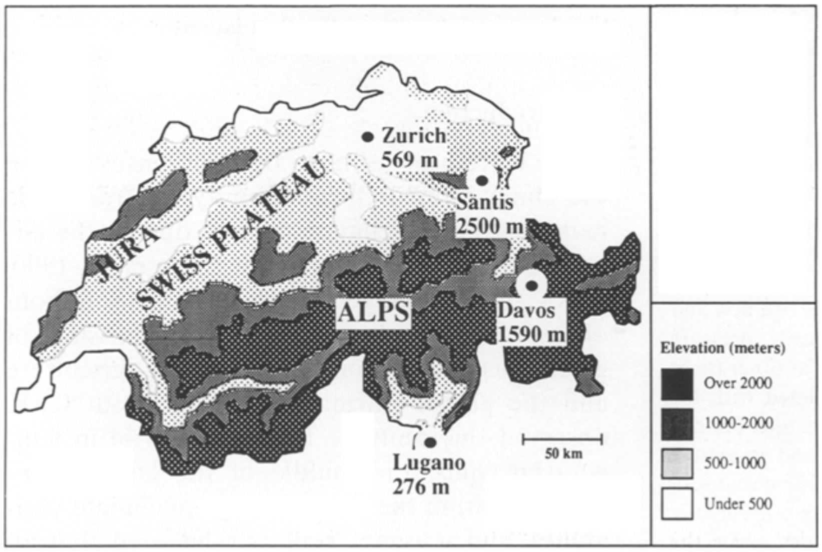

Fig. 1. Map of Switzerland showing the location of the four climatological stations

régimes, possibly leading to an amplification of the regional response of climate variables beyond the average changes estimated by the IPCC.

The climatological stations of Zurich (569 m above mean sea level), Säntis (2500 m), Davos (1590 m) and Lugano (276 m) have been selected on the basis of the length of their time series (uninterrupted daily records from January 1, 1901 – December 31, 1992) and their geographical location. The rationale is to identify, at least to a first order, whether there is a consistency in the data at the four locations, or whether they exhibit altitudinal or geographical particularities. Figure 1 shows the locations of these four stations in Switzerland.

The principal climatological variables studied include mean, daily maximum and daily minimum temperature, 24-hour precipitation sums (7 am to 7 am totals), relative sunshine duration (the proportion of sunshine duration with respect to its maximum possible site-specific duration), total snow depth, and pressure. Pressure is essentially determined by the synoptic scale and is far less sensitive to local and regional effects than temperature or precipitation; of the climatological statistics available for this study, pressure is the only variable capable of providing a link between the large and the regional scales.

When working with long time-series, the question invariably arises with regard to the homogeneity of a particular data set. Over a period as long as the 92 years investigated here, certain instruments have been changed or upgraded, the location of the instruments may have been shifted, the environment of the measurement site will certainly have experienced some modifications, and biases imposed by the different observers over the period of the record may enter into the data sets. Despite these constraints, it is generally recognized that the SCDB is one of high quality and reliability; for example, when instruments such as sunshine recorders were changed, the old and the new instruments were placed side by side for a period of several months for calibration purposes. Site changes have also occurred, in particular in Zurich in the 1950s; however, the temperature and pressure data sets contain corrections taking into account this change, in particular for the altitudinal differences between the old site and the present site. Although it could be argued that the time series at Zurich and Lugano will inevitably be contaminated by urban heat island effects, this does not appear to be a dominant feature of the series, since as will be seen, the increase of temperature at these locations is not significantly higher than at the mountain stations where the urban signal is absent. It should be furthermore noted that while the climatological stations at Zurich and Lugano are indeed located in an urban environment, both Lugano and, to a lesser extent Zurich, are small cities which do not exhibit the large urban sprawl characteristic of major industrialized cities and where the urban heat island effect is readily identifiable. Furthermore, as will be seen in the discussion, the data sets at the four very different study locations (in terms of their geography) exhibit a very large degree of consistency, indicating that for daily observations over a period of close to a century, contamination of the data resulting from one or more of the above-mentioned factors is relatively minor. The information provided by the SCDB can be considered to be at least as reliable as the data sets used to investigate global warming by other authors (Jones et al., 1986; Boden et al., 1990, to cite but two examples).

2.1 Analysis of Temperature Records

Temperature is one of the most widely used climatological variables in climate change and associated impacts studies, not only because it is one of the easiest to measure directly and to reproduce in numerical models but also because it is, with precipitation, one of the principal controlling factors on a wide range of climate-dependent environmental and ecological systems.

Figure 2 provides a graphical representation of the evolution of daily minimum temperatures at the four stations from the beginning of the century to the end of 1992. Based on the daily temperature values, mean annual statistics have been established; a five-year running mean has been applied in order to filter out some of the high-frequency modes inherent to the interannual variability. At all four stations, minimum temperatures have increased on average by about 2 K between 1901 and 1992, though the manner in which this warming is achieved is not homogeneous; the low-level stations (Zurich and Lugano) exhibit a continuous increase in temperature, whereas at Davos a considerable fraction of the increase in minimum

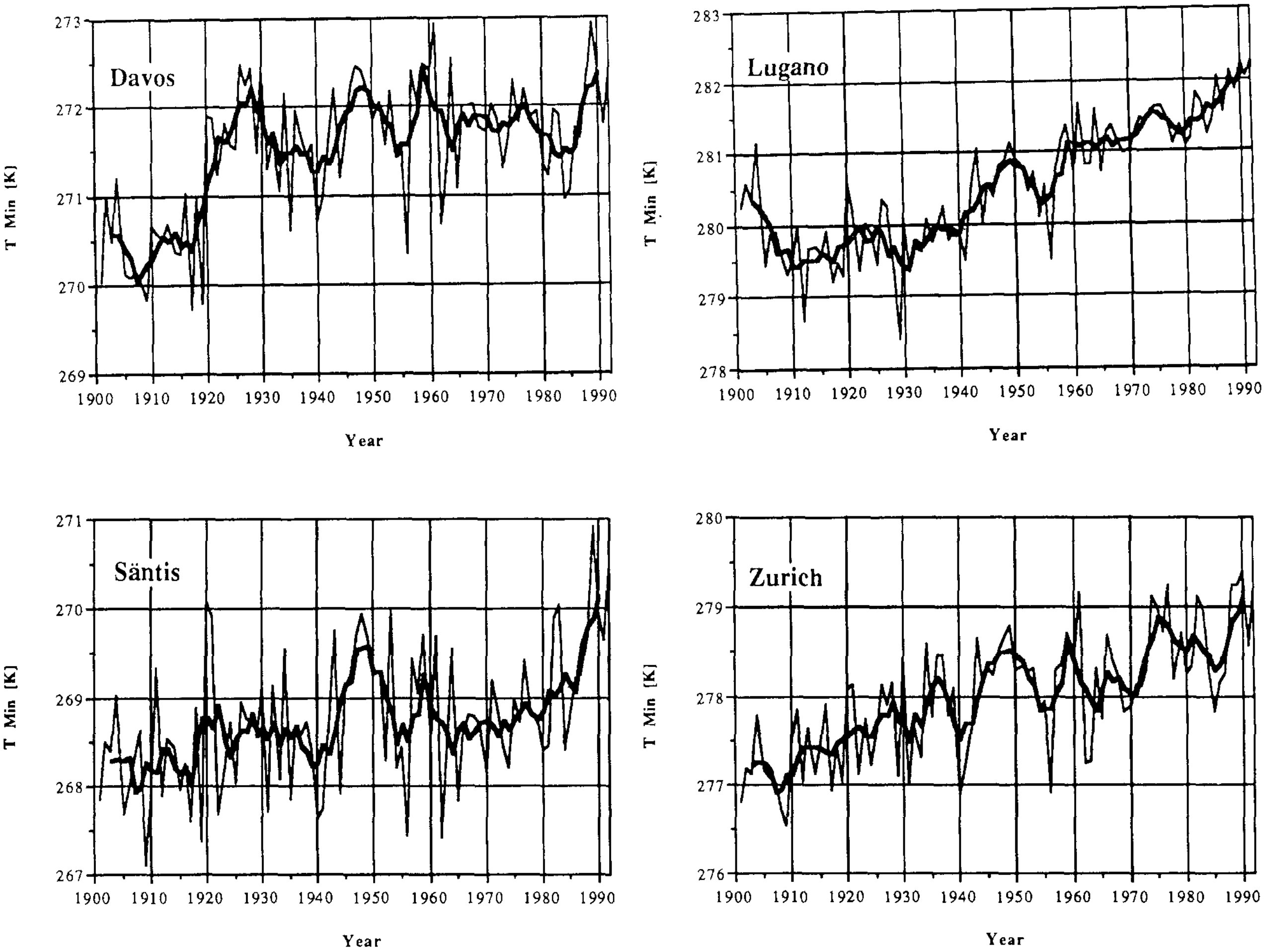

Fig. 2. Average annual daily minimum temperature trends, 1901–1992; the bold line represents a 5-year filter function to remove high-frequency fluctuations from the data

temperature had been attained by 1930 and has since then tended to oscillate around a quasi-constant value; at the high-elevation Säntis, warming has taken place in an accelerated manner in the decade of the 1980s. It should be noted that in all four records, an event lasting about 15 years occured from the early 1940s to the late 1950s, characterized by warming in the initial phase and cooling of similar magnitude towards the end of the event. Certain stations exhibit other long-term cycles of between 8 and 12 years' duration, but none is as clearly marked as the 1940–1960 departure.

Figure 3 illustrates the evolution of maximum temperatures at the four stations. At the low-altitude locations, maximum temperatures exhibit a decreasing trend especially between 1940 and 1980 of between 1 and 2 K. In Davos, maximum temperatures remained essentially unchanged up till 1940 then underwent a series of major decadal-scale fluctuations. Säntis maxima exhibit very similar behavior to the minima, with a strong increase of maximum temperature in the 1980s. The major departure beginning in the early 1940s, present in the minimum temperature records, is visible here also.

Because minimum temperature trends are different from those of maximum temperatures, the diurnal range of temperature has tended to decrease at all stations; in Zurich, for example, the daily temperature range on an annual average basis exceeded 9 K at the beginning of the century and has dropped to about 7.5 K today. The fact that the diurnal range and annual variance of temperature is decreasing has been reported in other data analysis studies for Northern Hemisphere locations (e.g., Karl et al., 1984), and therefore provides some degree of consistency between the Swiss

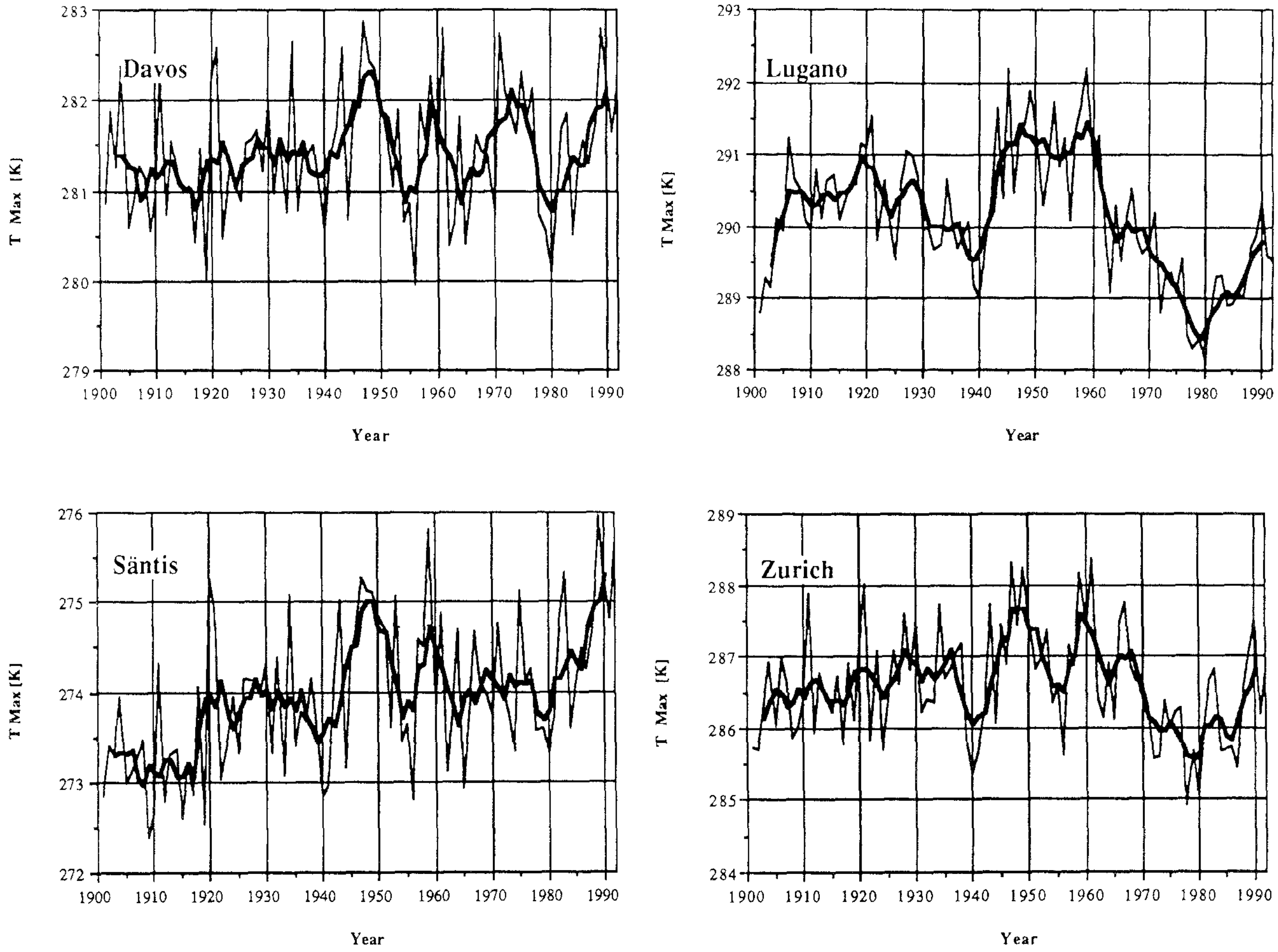

Fig. 3. As Fig. 2, except for average annual daily maximum trends

data and other regional or supra-regional data. It is also consistent with model studies of greenhouse-gas induced warming, where the major effect would indeed be on nocturnal temperatures, even though these model simulations generally tend to understimate the trapping of terrestrial radiation by greenhouse gases (Rind et al., 1989).

2.2 *Analysis of Precipitation Records*

The analysis of precipitation is made difficult by the fact that the daily precipitation data (24-hour precipitation sums) available on the SCDB are raw, uncorrected data. It is well-known that for technical reasons, precipitation at high mountain elevations can be underestimated by as much as a factor of 2 (e.g., recent papers by Kirchhofer and Sevruk, 1992; and Sevruk et al., 1993). The instrumental errors are often linked to microscale dynamics in the highly complex orography in the vicinity of a high-elevation station, where strong eddies and accelerating airflow over mountain crests determine the manner in which precipitation will be intercepted by a rain-gauge. Additional problems related to discontinuities in precipitation measurements resulting from even minor site changes and instrument changes contribute to the uncertainties in precipitation measurements. The measurement site in Zurich changed in the 1950s and the daily precipitation records have certainly been affected as a consequence. However, use of yearly precipitation totals to some extent alleviates this problem, as these values will in general be representative of more than just their immediate measurement environment (the exception being if much of the precipitation is in the form of convective precipitation whose intensity can vary considerably within very short distances). Civil engineering work at the summit of Säntis in the last few years will also have inevitably contami-

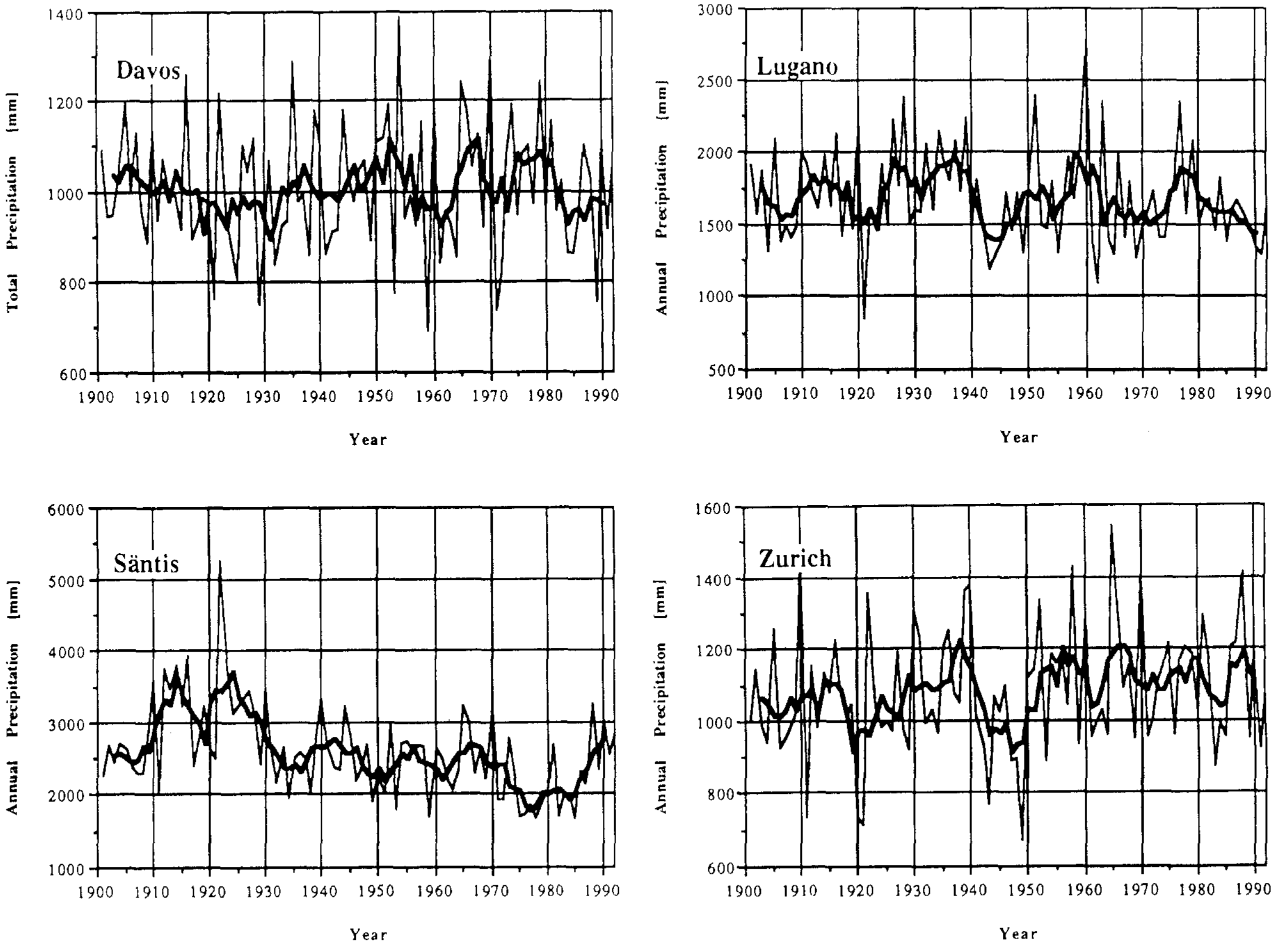

Fig. 4. As Fig. 2, except for average annual 24-hour precipitation trends

nated the precipitation data, so that the Säntis records are given here without any guarantee as to their statistical validity in the trend analysis. Corrections are at present possible for monthly and yearly precipitation values but not for daily data, nor consequently for the daily extremes which are probably the most important control parameter on a wide range of systems. For the purposes of this paper, however, the precipitation data still have a measure of usefulness in bringing to light certain aspects of secular changes in regional climates.

Figure 4 illustrates the annual precipitation totals based on the daily 24-hour totals; in Davos, Lugano, and Zurich, there is no significant trend over this century, and the low-frequency curves exhibit cycles on a 10–20 year time scale around a relatively constant mean value. Precipitation records at Säntis exhibit a decreasing trend from the early 1920s to the late 1980s with an increase in the last decade; due to problems of measurement inherent to high-elevation stations, the tendencies shown here may be as much the result of instrumental error as a physically-based climatological signal.

All four stations exhibit very noisy precipitation time-series, reflecting the strong interannual variability in the Alpine region. Precipitation may be triggered by a number of mechanisms, which occur on different time and space scales, from the large synoptic scale associated with the passage of a frontal system to the very local influence of orography or convection (which themselves may be amplified by synoptic disturbances). As a result, it is very difficult to decouple one effect from another solely on the basis of annual values; it is consequently equally difficult to determine any particular trend associated with global warming, for example.

Extreme precipitation amounts, i.e., the highest 24-hour precipitation total, also exhibit a very strong interannual variability and no significant

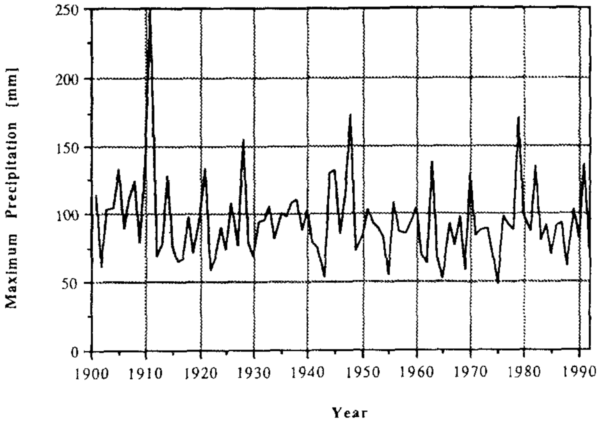

Fig. 5. Maximum precipitation trends for Lugano, 1901–1992

trends. Figure 5 shows the record of extreme for Lugano, where episodes of precipitation in excess of 100 mm/day (generally associated with strong downpours in unstable convective situations) are, if anything, less frequent than in the early part of the record.

2.3 Analysis of Sunshine Duration Hours

Relative sunshine duration hours may be defined as the percentage of sunshine duration intercepted by a sunshine recorder relative to the total possible sunshine duration. This parameter is dependent not only on the season but also on site-specific features, such as the location of the climate station in the vicinity of mountains or other obstacles which would mask the sun (i.e., the sky-view factor).

Figure 6 illustrates the relative sunshine hours for the four climatological stations. With the exception of Säntis, a general decrease of annual mean sunshine hours is observed. A logical conclusion for the trends of maximum temperature is that the decrease in maxima observed elsewhere than Säntis could be explained by this decrease in

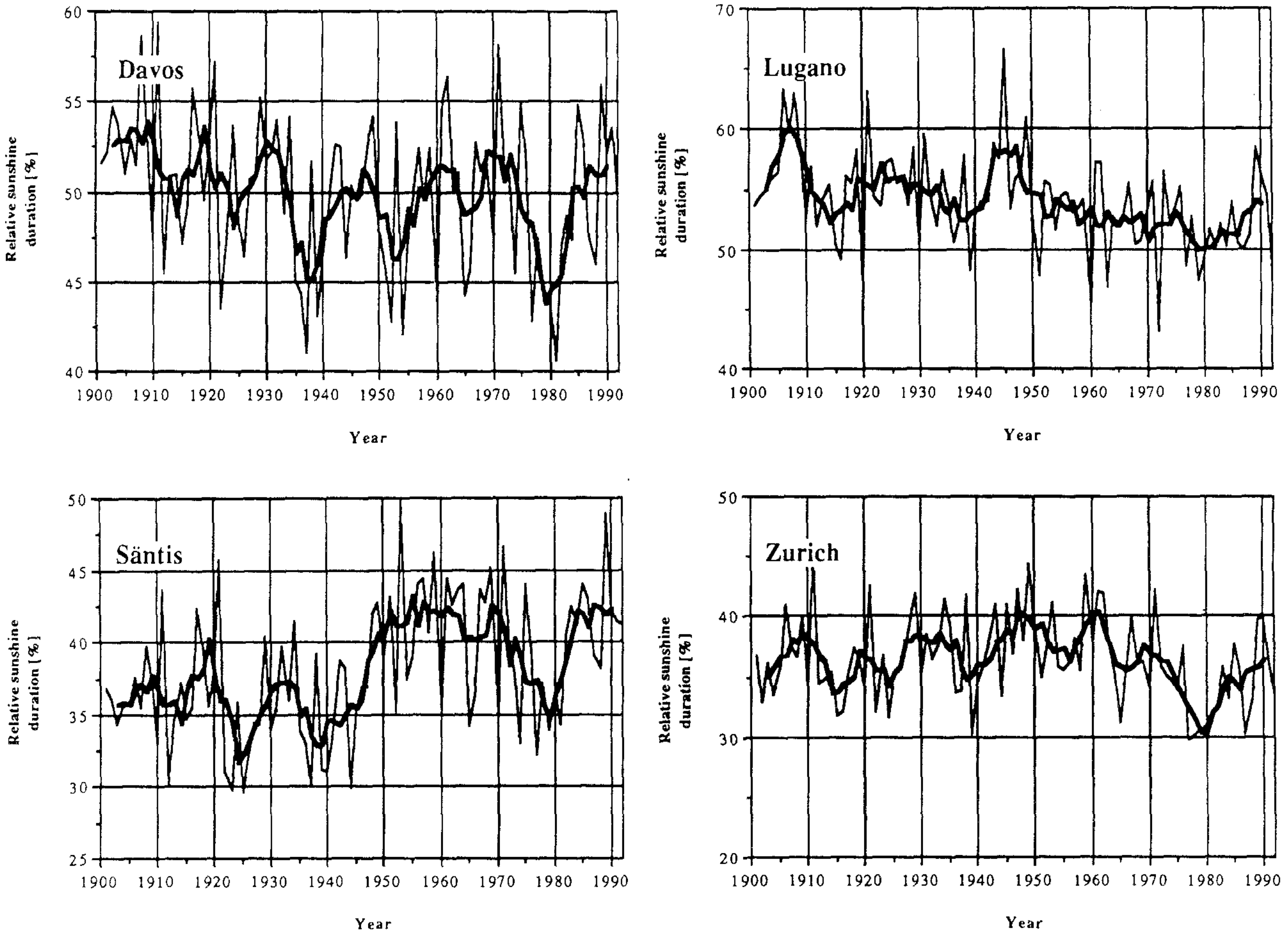

Fig. 6. As Fig. 2, except for average annual sunshine duration trends

sunshine hours: furthermore, in the absence of nocturnal cloud amount, the values of relative sunshine hours point to an increase in cloudiness over Switzerland. It could be hypothesized that cloudiness would persist during the night hours, thereby trapping outgoing infrared radiation and resulting in the observed increase of minimum temperatures. At all stations, sunshine increased in the 1980s, reaching average values not experienced since the early 1970s (i.e., the dip in relative sunshine amounts was one of the most marked and persistent periods in the record between 1970 and 1990).

2.4 Analysis of Snow Records

Snow is a particularly important feature in the Alps because it is a controling factor on a wide range of systems, ranging from hydrology to ecosystems. Its presence or absence may in many cases determine the evolution of plant species during their annual growing period, or the runoff and flow in many of Europe's major river systems. The amount and duration of snow in the Alps also has economic significance in terms of tourism and hydro-power in particular.

Figure 7 gives an overview of the occurrence of snow cover in Davos during the period from 1931–1992, for three thresholds of total snow depth (25, 50, and 75 cm respectively). Snow records in digital form unfortunately do not start until 1931; in this figure, the year 1931 should be understood as the winter season beginning in the fall of 1931 and stretching into the spring of 1932. The extreme right-hand record is for the winter of 1991–1992. The principal comment which can be made with respect to snow depth is that, even in a high-altitude resort such as Davos, there is a significant interannual variability. All winters in the period have experienced at least the minimum threshold of snow cover (25 cm), but snow has been more abundant in certain years, in particular in the early 1950s, the mid 1960s and mid 1970s, and the early to mid-1980s. The lack of snow in the latter part of the 1980s, culminating in the winter of 1989–1990, which raised considerable media interest and led to financial difficulties for low-altitude resorts, was not in itself an exception. There have been periods (1931–1934; 1964; 1971–1972; 1978–1979) in which snow has been lacking in terms of snow duration and abundance.

One explanation for the increasing concerns in mountain communities regarding periodic lack of snow may be found in the human perception of climate. During the 1960s, snow was generally present and, in terms of snow depths was perhaps more abundant than in recent years. As this was a boom period for mountain resorts and a time when investments in tourist infrastructure were high, that particular decade was regarded as the

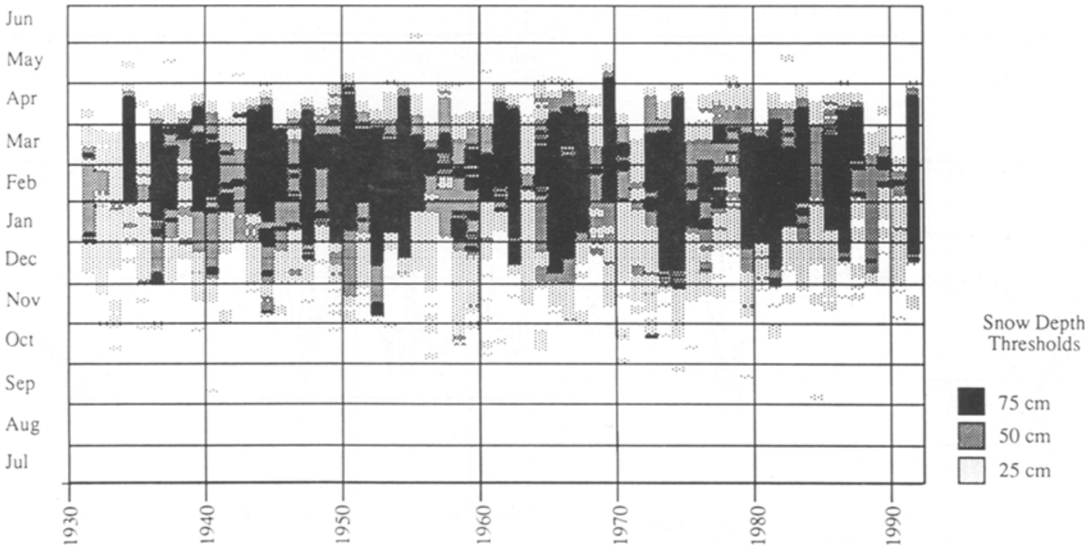

Fig. 7. Time-frequency diagram of snow depths in Davos for 25, 50 and 75 cm thresholds. The vertical extent of the bars corresponds to the duration of the events

norm as far as winters are concerned. The data analysis shown here suggests that, in the present sampling period, the decade of the 1960s was rather the exception in terms of snow abundance, and certainly the 1940s were marked by less snow duration and less snow depth than the 1980s, widely regarded as anomalous in the sense of lack of snow. The cultural and perception factors have been widely surveyed by Rebetez (1994) and shed light on climate issues in Switzerland.

2.5 Analysis of Pressure Records

The analysis of surface pressure allows a link to be made between a climatological variable which is essentially representative of synoptic-scale atmospheric processes, and those other variables just described, which are generally more representative of the regional and local scales. The discussion will focus on pressure in Zurich only, since the geographical variability of pressure in an annual average context is small; this is illustrated in Fig. 8, where the pressure measured at Zurich is highly correlated with that at Lugano (and Basel and Neuchâtel, in order to justify this point). Because pressure is an integral value which describes the mass of the atmosphere above any particular point, it is only in short-lived circumstances that a strong pressure gradient will occur between adjacent locations over a region as small as Switzerland. High-frequency pressure differences characteristic of different weather situations (passage of frontal systems, foehn situations, etc.) where the pressure gradient across the Alps can be high, are filtered out when analyzing mean annual data. The pressure data measured at the Zurich station can therefore be considered representative of the large-scale pressure field over Switzerland.

Figure 9 illustrates the evolution of average surface pressure measured at Zurich, i.e., not reduced to its sea-level value. It is seen that for most of the century, the low-frequency component of pressure (5-year running mean) has fluctuated within the range of 949–951 hPa. Since the beginning of the 1980s, however, the pressure field has exhibited a totally anomalous behavior, in that it has increased continuously to reach values beyond 952 hPa. The 952 hPa annual average level was reached only four times previously this century, but since 1987 has exceeded this value and has continued to increase into the 1990s. This remarkable increase of pressure in the latter part of the record is related to a greater frequency of blocking high pressure episodes in the Alpine region, as will be seen later in the discussion pertaining in particular to Fig. 14. At no other time in the record has the rise in surface pressure been as long and uninterrupted in the 5-year average curve, nor has the amplitude of the increase been as large. This fact is reflected in Fig. 10, where the entire distribution of pressure has shifted in the decade of the 1980s with respect to the long-term 1951–1980 climatological mean. It is not just one part of the frequency distribution which is changed but the entire probability density function; it retains its original shape and amplitude and is shifted to higher pressures by almost 3 hPa. While one obvious conclusion is that this may be the result of instrumental error, very similar density func-

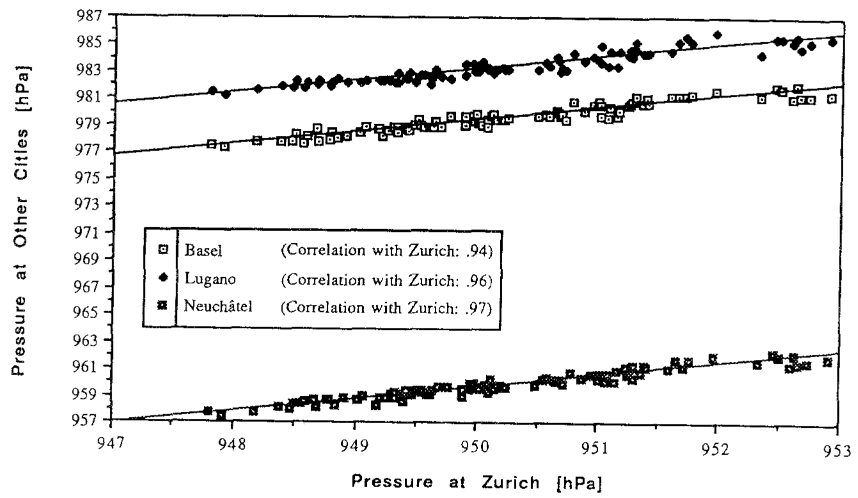

Fig. 8. Comparison of annual average pressure between Zurich, Lugano, Neuchâtel and Basel

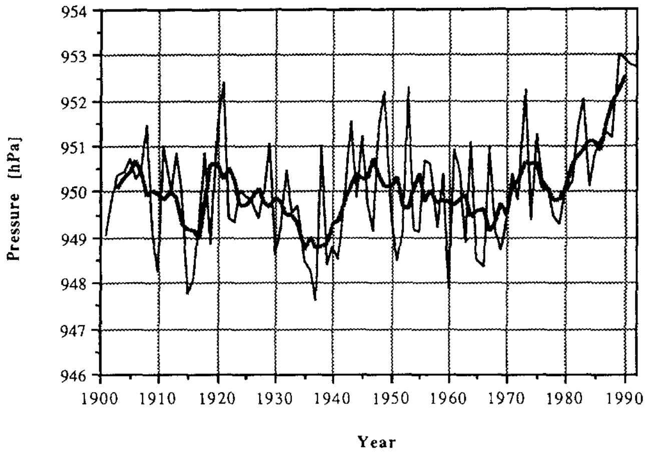

Fig. 9. As Fig. 2, except for annual average pressure trends

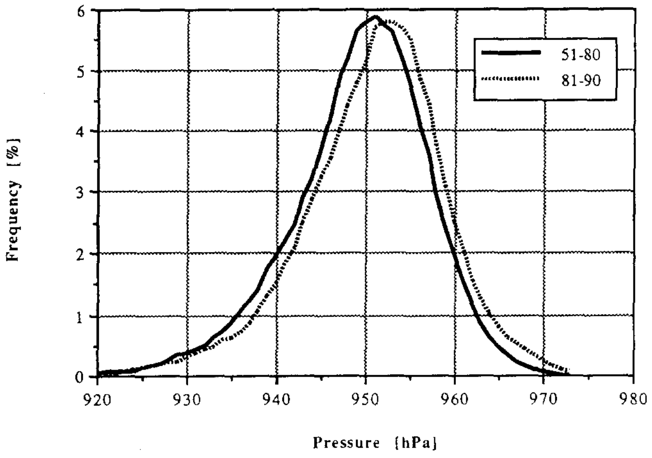

Fig. 10. Difference in pressure distribution in Zurich in the 1980s compared to the long-term climatological average (1951–1980)

tions have been observed at other climatological stations where pressure is recorded (e.g., Lugano, Neuchâtel, and Basel), thereby confirming the physical nature of this result. The change in the density function seen in this figure may be indicative of a shift in the relative occurrences of typical weather régimes over the Alpine region in recent years, i.e., a manifestation of climate change over the Alps.

3. Links Between Global-Scale Climate Records and Regional Data in Switzerland

3.1 Temperature Trends in Switzerland Compared to the Global Record

As a means of feeding into the next section concerning possible causal relationships, it is of interest to see the extent to which the temperature trends observed in the Swiss data are consistent with global trends, despite the many uncertainties inherent in both the instrumental record and model simulations.

For comparison purposes, the Swiss data are presented in the same manner as the Jones et al. (1986) analysis, i.e., in the form of anomalies from the 1951–1980 climatological average. The results are illustrated in Fig. 11. What stands out clearly in this figure is that the amplitudes on the regional scale are much larger than on the global scale. The Swiss data are characterized by a number of periods of significant temperature fluctuations, lasting between 8 and 15 years approximately. In some cases, the Swiss data are out of phase with the global record (in the 1940s, 1960s and 1970s). Since the mid- 1980s, the increasing temperature trend for the Swiss records is synchronous with the global warming trend, and the rate of warming far exceeds that of the global tendencies. The Swiss data indicate that the 1940s were the warmest decade of this century, more so than the 1980s.

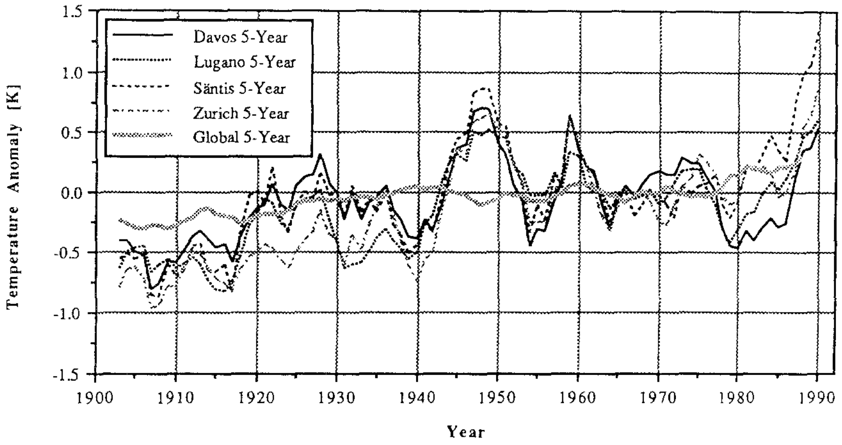

Fig. 11. Comparison between Swiss mean temperature anomalies and global temperature anomalies, 1901–1992. All data have been smoothed with a 5-year filter. Global data from Boden et al. (1990)

Table 1. *Warmest Years of the Century, in Decreasing Order for Davos, Lugano, Säntis and Zurich, with Deviations from the 1951–1980 Climatological Mean*

Davos		Lugano		Säntis		Zurich	
Year	Anom.	Year	Anom	Year	Anom.	Year	Anom.
1961	1.31	1943	0.91	1989	2.04	1990	1.36
1947	1.21	1949	0.90	1992	1.74	1961	1.16
1989	1.11	1990	0.89	1920	1.34	1949	1.05
1934	0.81	1861	0.79	1983	1.32	1947	0.97
1948	0.80	1945	0.70	1959	1.24	1959	0.95

In terms of record temperatures, Table 1 shows that among the five warmest years of the century, only one lies in the 1983–1992 period at Davos, Lugano, or Zurich, unlike the global record, where six of the warmest years of the century occur between 1983 and 1992 (Houghton et al., 1992). The exception here is Säntis, where indeed three of the warmest years are recorded in 1983, 1989, and 1992, with very significant departures from the 1951–1980 climatological mean. The five coldest years, in terms of their annual average, are generally confined to the first twenty years of the century, with the exception of 1956 which experienced a very cold month of February, with temperatures below freezing (even for maximum temperatures) throughout the month; in Zurich, the monthly mean maximum temperature was 9.4 K below the 1951–1980 norm for February, and the mean monthly minimum was 11.2 K below the norm. This cold spell was confined to the part of Switzerland located to the north of the Alpine chain, as can be deduced from the Lugano records which do not include 1956 among the statistics for the 10 coldest years. In terms of record-breaking temperatures for an individual day, the years 1985 and 1987 are amongst the coldest at all locations except for Lugano. With these notable exceptions, however, there is no doubt that the beginning of the century was on average colder than the latter part of the record.

There have been a number of studies of trends on global, hemispheric, and continental scales, many of them linked to the IPCC process. These studies have been instrumental in highlighting some of the features of observed climate variability through exhaustive data analysis (Jones et al., 1986; Jones, 1988; Jones and Kelly, 1983; Jones and Wigley, 1990; Jones et al., 1990; Wigley and Jones, 1981; Wigley and Raper, 1990; see also Boden et al., 1990, for the Oak Ridge National Laboratories data base on global warming). These pertain essentially to globally – or hemispherically – averaged temperature and precipitation data, with ad-hoc correction for site changes and the thermal influence of urbanization. A first-order analysis of global or hemispheric data emphasizes the rise in average temperature since the beginning of the industrial era, with a slight cooling between the

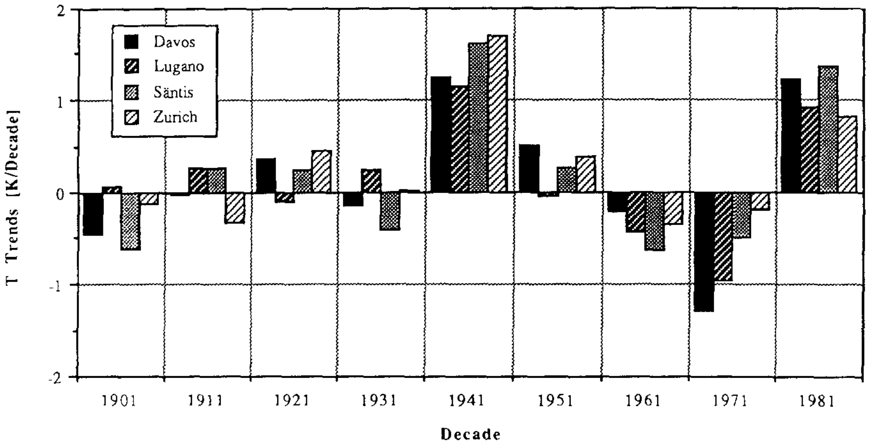

Fig. 12. Decadal warming rates for mean temperature records in Switzerland

1940s and the 1970s. It is of interest to analyse whether the global signals of climate change this century are also discernible in the Swiss data. Figure 12 provides a decade-by-decade illustration of the warming rates of average annual temperature for this period at all the locations studied. It is seen that until the 1940s, the rate of change of temperature per decade was on the order of 0.5 K or less, without any particular consistency of the sign of the temperature change according to the location, i.e., two stations can be seen to be in phase one decade and out of phase the next. In the 1940s, however, a very significant change occurred, with all four stations exhibiting the strongest warming of the century, exceeding 1.5 K/decade at Säntis and Zurich (i.e., more than 3 times the previous warming or cooling rates). This sudden jump in the warming trends has resulted in some of the warmest years in terms of their annual average, as seen in Table 1. The warming is much less pronounced in the 1950s and reverts to a cooling in the 1960s and 1970s, reaching or exceeding 1 K/decade. The 1980s exhibit a return to strong warming, around or above 1 K/decade. When combined with the strong warming of the 1940s, the net effect over the period of record is a warming, since the cooling trend in the 1960s and 1970s does not compensate for strong warming of the 1940s and the 1980s. The analysis undertaken by Balling (1992) to the effect that most of the 20th Century warming occured in the first half of this century in the Northern Hemisphere does not appear to be the case for the Swiss records; strong warming has occurred in two distinct decades, namely the 1940s and the 1980s. The beginning of the century is characterized by small warming/cooling rates while the latter part exhibits larger rates of temperature change.

3.2 Possible Causal Mechanisms of Observed Climate Change in Switzerland

There are numerous studies in the literature which attempt to link observed climate variability at certain locations in space with parameters representative of the atmospheric general circulation and variations of those parameters. The work done on the ENSO phenomenon and the definition of the Southern Oscillation Index (SOI) has brought to light the dependence of precipitation régimes in the Pacific region (Indonesia, Oceania, South and Central America), for example, to changes in the SOI (Bjerknes, 1969; Barnett, 1978; Diaz and Markgraf, 1991 among many others). Research into climate variability in the Northern Hemisphere has been conducted by a number of researchers on the basis of the Pacific/North American (PNA) teleconnection patterns (*inter alia,* Trenberth, 1990; Hansen et al., 1993; Wallace and Zhang, 1993). Hansen et al. (1993) note that blocking events over Europe have contributed disproportionately to large departures from normal regional surface pressure, temperature, and precipitation. As will be demonstrated here, the fact that most of the anomalous mid-troposphere circulation events occur during the winter season (from November through March) means that the climate variables on the regional scale should exhibit more anomalous behavior in this period than during the summer months. Indeed, studies of hemispheric climate trends show that much of the average surface air temperature increase is associated with wintertime warming, especially over the high-latitude continents (Jones and Briffa, 1992).

This interplay between global or hemispheric forcings and regional climate response will be further discussed in the next section, but we shall first present the conclusions regarding the link between the time series of pressure as measured in Zurich which, for reasons justified in the previous section, can be considered to be representative of the large-scale pressure field over the region. The index chosen as indicative of the synoptic-scale is the North Atlantic Oscillation Index (NAO). The NAO Index is the difference in sea-level pressures between Punta Delgada in the Azores and Akureyri in Iceland; it is a measure of the strength of the Westerlies over the North Atlantic. If the NAO Index anomaly with respect to the 30-year climatological mean period (1951–1980) is positive, then this is indicative of a higher-than normal occurrence of Westerly winds across the North Atlantic.

Figure 13 shows the relationship between the wintertime (DJF) anomaly of the NAO Index and that of the Zurich DJF pressure anomaly. In both cases, the strong decadal variability can be observed with fluctuations in both anomaly sets lasting about 20 years through to the end of the 1960s. The apparent regularity which has prevailed until this time, changes considerably after the early 1970s, after which the fluctuations are of shorter duration; more significantly, there is a marked upward trend towards strong positive anomalies, particularly for the Zurich data set. While the two DJF curves bear a remarkable similarity, a more detailed analysis of the two data sets highlights an even more interesting phenomenon: the low correlation in the first part of the record and also between 1951 and 1970, the higher correlation in the period 1931–1950, and the highly significant correlation in the last 20 years of the record. The correlation coefficient between the two curves for four twenty-year periods is given in Table 2, along with the significance of the t-test at the 1% significance level. The present analysis emphasizes the fact that a switch has occurred in the general circulation patterns over the Alpine area (more probably over Western Europe, which then impacts on flow patterns over and around the Alps), with alternation between pressure fields embedded in a zonal flow described by the NAO index and those in which the pressure field is controlled by other large-scale circulation patterns. The periodicity is on a time-scale of about 20 years according to Table 2, and confirmed by Fig. 13.

Table 2. *Correlation Between the North Atlantic Oscillation Index (Dec/Jan/Feb values) and the Observed DJF Surface Pressure at Zurich for Different Periods of the Record;* significance test is at the 1% level

Period	R	Significance
1911–1930	0.241	Low
1931–1950	0.656	High
1951–1970	0.176	Low
1971–1990	0.847	Very High

Figure 14 presents a time-frequency distribution of high pressure events over Switzerland, based on the Zurich records; the 965 hPa threshold level has been selected (this is approximately equivalent to a sea-level-reduced pressure value of 1030 hPa). The graph shows the persistence pattern of high

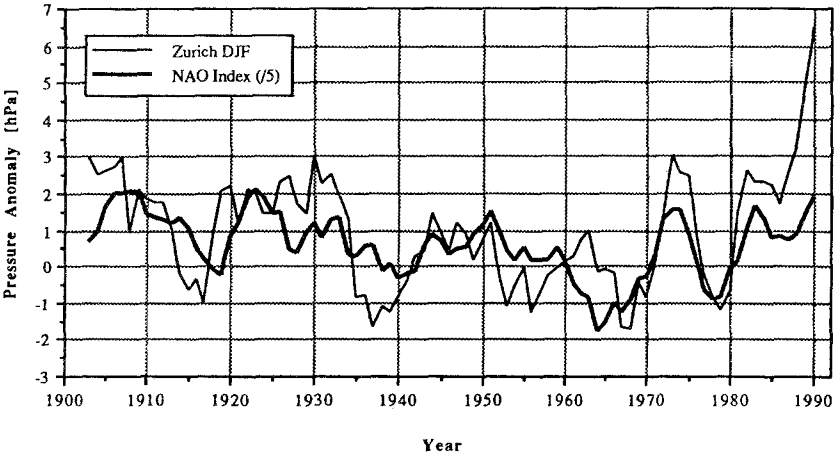

Fig. 13. Comparison between the wintertime (DJF) anomaly of the North Atlantic Oscillation Index and the anomaly of the DJF surface pressure in Zurich

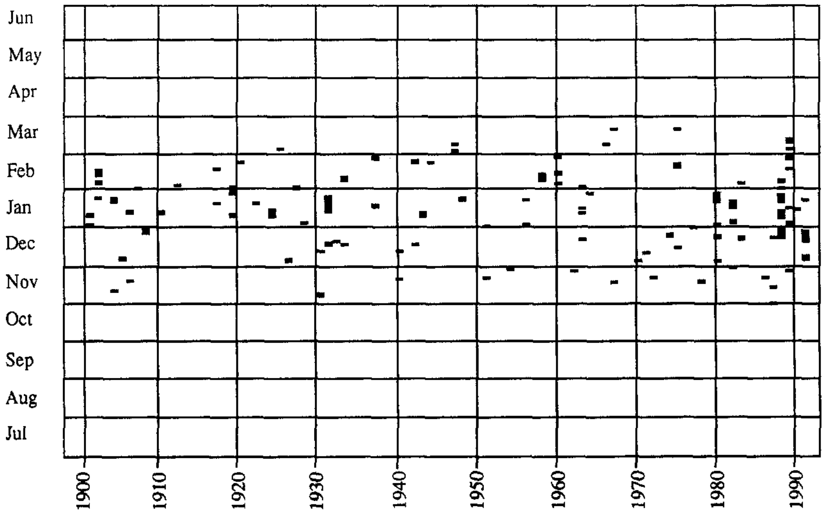

Fig. 14. Time-frequency diagram of high-pressure events in Zurich for the 965 hPa threshold. The vertical extent of the bars corresponds to the duration of the events

pressure episodes, and extended periods of blocking highs can be identified, especially towards the end of the record. Based on this graph, statistics for persistence have been established and are presented in Table 3.

The table implies to some extent that periods in which the NAO Index anomaly is positive are accompanied by above-normally persistent periods of high pressures. Furthermore, in the 1980s, where the increase in surface pressure over Switzerland is quite remarkable, the blocking highs are far more frequent than at any other time of the century, with a decadal frequency 2–3 times greater than during the previous decades; the 1980s account for almost 25% of the total observed blocking highs this century. Indeed, 1989 is a record-breaking year with 30 days of persistent high pressure beyond the 965 hPa threshold, followed by 1990, 1991, and 1992. This sequence of four successive years accounts for over 16% of the blocking episodes this century.

Table 3. *Average Persistence of High Pressure Situations in Zurich* (days/year for the 965 hPa level)

Decade	Persistence
1901–1910	6.3
1911–1920	5.6
1921–1930	5.3
1931–1940	5.9
1941–1950	5.8
1951–1960	3.2
1961–1970	4.5
1971–1980	4.9
1981–1990	11.6

It should be stressed that a strong positive NAO Index can result from either a deepening of the Icelandic Low or a strengthening of the Azores High; synoptic chart evidence for the 1980s suggests that the positive NAO Index in the 1980s is linked to an extension of the Azores High into southern and central Europe, thereby explaining the persistence of periods of high pressure in the winter months over the Alps; baroclinic activity over the North Atlantic is deflected over more northerly latitudes of Europe. A deepening of the Icelandic Low, on the other hand, which can lead to similar positive values of the North Atlantic Index, appeared to be a more common occurrence in the years between 1930 and 1950. This led to more westerly flow régimes over the Alpine region and thereby to a lower occurrence of blocking high episodes than in the 1980s. This short analysis helps to explain the reason why, for similar values of the NAO Index, the response of surface pressure over Switzerland can be considerably different.

Some attempts to quantify the possible effects of ENSO on regional data have not been successful, although the fact that in the 1980s three tropical Pacific Warm Events occurred with no Cold Events in between (Trenberth, 1990) raises questions as to the possible influence of events far removed in space on regional climatological processes in Switzerland; the signal-to-noise ratio in the data which has been analysed is too low for any meaningful conclusions to be reached. It suffices here to have established a distinct link between the synoptic and regional climatological scales, by showing that there is a periodic transition between zonal dynamics and other régimes approximately every 20 years; it is beyond the scope of this paper to enter into the possible causal effects of the exceptional blocking high pressure episodes from 1989–1992.

4. Response of Climate on the Regional Scale to Larger Scale Régimes

The periods of lowest and highest frequency of blocking episodes (which coincide with the lowest and highest correlations between the NAO Index and the Zurich time series of pressure), respectively 1951–1960 and 1981–1990, will be analyzed in this section. Figure 15 provides an illustration of the changes in the daily pressure field which have occurred between these two decades; the curve is obtained by subtracting the decadal-average daily pressure values for the 1950s from those of the 1980s. It enables one to identify the shifts in pressure anomalies throughout the year. This, and subsequent figures for other climatological variables have a 5-point filter applied to the data in order to remove high-frequency noise.

It is not surprising from the discussion on mean pressure tendencies to see that at almost all times, pressure is systematically higher in the 1980s than in the 1950s; this figure highlights the fact that the pressure increase in the 1980s over the 1950s occurs particularly in the fall and winter months (early November to late March), with anomalies reaching up to 8 hPa; in the spring and summer months, the pressure excess in the 1980s is much more modest and there are even periods of negative pressure anomalies from April to June.

It can be expected that the sensitivity of the different climate variables will be felt more strongly during the winter season than during the rest of the year. However, the relationship between pressure and other variables is not quite as straightforward and it is worthwhile giving in this context a brief qualitative description of a rather unique feature of regional climate in winter under high-pressure conditions in Switzerland. Very often, extended periods of high pressure are characterized by a cold air pool trapped above the Swiss Plateau, i.e., that part of the country located between the Jura Mountains and the Alps (Fig. 1), stretching from the Lake of Geneva in the SW to the Lake of Constance in the NE. The average elevation of this zone range from 400–700 m, and the depth of the cold air pool averages between 100 and 600 m; the upper boundary is characterized by a sharp temperature inversion, and this discontinuity is generally marked by the top of stratus formed by condensation of moist air trapped within the cold air pool. In the calm dynamic situation of a high-pressure system, the cold air has difficulty in evacuating out of the Swiss Plateau because of the bordering orography; the Jura and the Alps converge in the region of Geneva and act as a physical barrier to the cold air outflow. It is only with the advent of a perturbed synoptic régime that the cold air pool may be broken up. Above the inversion and the fog or stratus layer, conditions are usually very clear in the mountains, and can be relatively mild during the day because of the subsidence of air within the high-pressure system. Because of reflected solar radiation at the top of the stratus layer, conditions beneath the stratus may be colder

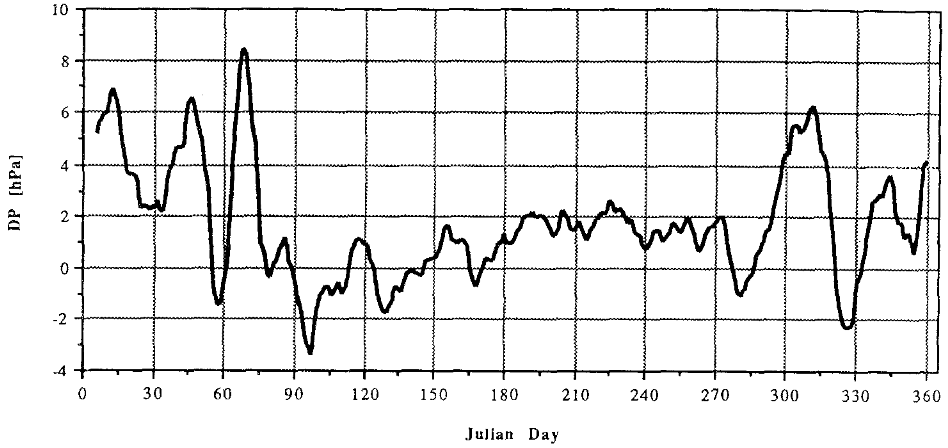

Fig. 15. Difference in average (ten-year means) daily pressure in Zurich between the 1980s and the 1950s

during the day in Zurich, Bern, or Geneva, than they are at high-elevations such as Davos. At night, temperatures in the higher elevations will usually be cold as a result of strong radiative loss to space which more than offsets the subsidence warming; below the stratus layer, temperatures will not change very much from their daytime values because of the opaqueness of the stratus clouds to outgoing infrared radiation.

4.1 Response of Temperature

An analysis of the distribution of temperatures in terms of their frequency of occurrence over a given period of time serve to highlight the manner in which changes are achieved. In Fig. 16 the distribution of daily minimum temperatures at Lugano is seen to be shifted by +2 K and more in the 1980s compared to the 1950s. Other stations exhibit similar translation in the minimum temperature distribution between the two decades, with amplitudes which are comparable at Säntis and somewhat lower in Zurich and Davos. The analysis of the distribution of minimum temperatures shows that the warming occurs at all points in the distribution, i.e., no particular part of the frequency distribution exhibits stronger warming than another, but rather the entire set of frequencies is shifted by the average minimum temperature change occuring between the 1950s and the 1980s.

Average annual maximum temperatures are seen to be either decreasing (as at Lugano) or increasing at a much lower rate than minima (as at Säntis); an analysis of the frequency distributions of maximum temperatures has brought to light a difference in the manner in which the change in climate between the two decades affects the range of temperatures at each station. Lugano is perhaps the only station which exhibits a similar behavior to the minimum temperatures, i.e., a shift of the entire distribution towards lower temperatures. At Davos and Säntis, however, the left-hand part

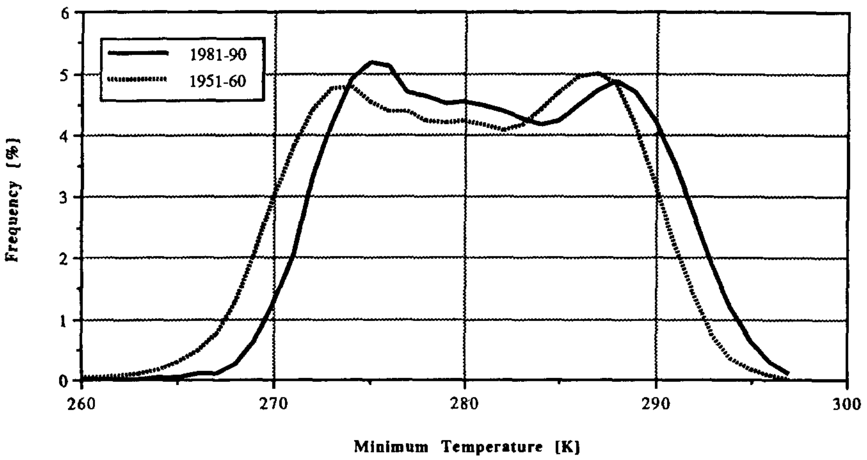

Fig. 16. Difference in daily minimum temperature frequency distribution in Lugano between the 1980s and the 1950s

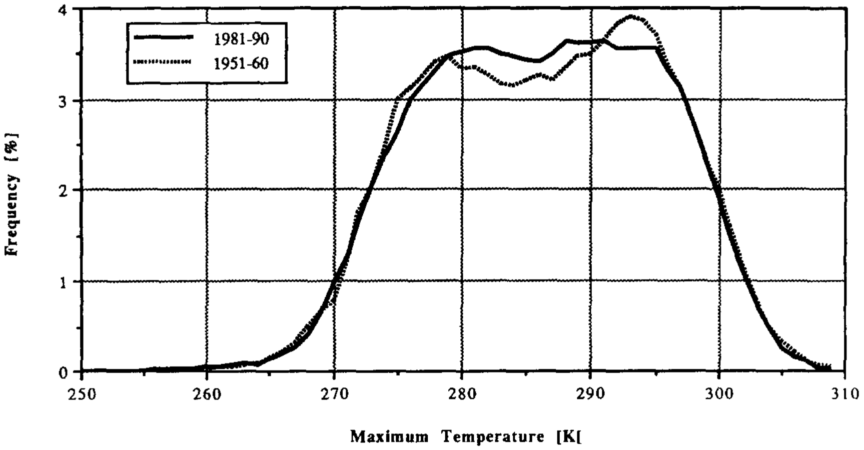

Fig. 17. Difference in daily maximum temperature frequency distribution in Zurich between the 1980s and the 1950s

of the distribution (the coldest temperatures) remain relatively untouched by the change in climate which has intervened between the two decades, at the expense of a redistribution of maximum temperatures around the median and the right-hand part of the distributions. In Zurich (Fig. 17), it is seen that the extremes of temperature remain unchanged, but that the decadal-scale temperature change has taken place in the central part of the distribution. The 1950s exhibit two flat peaks in the frequency around 279 K and 293 K, which have been smoothed out in the 1980s; the overall change represented by an integral value of the frequency distribution is seen to be relatively small.

While these figures allow somewhat more insight into the manner in which changes have occurred by analysing not only a mean change in annual values but also the change across the range of temperatures, it is also useful to investigate the manner in which climate change between the 1950s and the 1980s has occurred in time over the year. Figure 18 gives an analogous description of minimum temperatures to the pressure anomaly given in Fig. 15, i.e., a difference of decadal averages of daily minimum temperature between the 1980s and the 1950s. The annual distributions for all four stations have been plotted simultaneously. From previous analyses, it has been shown that minima have risen substantially between the 1950s and the 1980s, and an integral value over time for the four curves would simply confirm this fact. Figure 18 shows that much of the warming occurs in the early fall and in the winter months. Except for Lugano, some periods exhibit an average cooling, such as April, June, or December. The figure underlines the complexity of the manner in which warming occurs between the two selected decades; oscillations in the temperature anomaly show a monthly to bi-monthly periodicity, with amplitudes of the most outstanding cycle (January/February) ranging from 1.5 K at Lugano to 5 K at Säntis. In general, the amplitude of the oscillations increases with height.

Table 4. *Correlation Analysis Between the Data Sets Given in Fig. 18*

Correlation between:	R
Zurich – Davos	0.769
Zurich – Lugano	0.593
Zurich – Säntis	0.661
Davos – Säntis	0.747

Table 4 provides the correlation coefficients for the different data sets. The correlation between these curves is high between Zurich and Säntis and Davos, and somewhat lower between Zurich and Lugano; between the two higher altitude stations, the correlation is particularly high. The correlation analysis serves to illustrate that, at least to the north of the Alps, the same basic processes are taking place; the weaker correlation with the Lugano data, which will be seen to be systematic, is indicative that Lugano is more clearly subjected to other climatic régimes, in particular Mediterranean influences, than the other stations.

Figure 19 is analogous to Fig. 18, but represents the anomalies of maximum temperatures for all four stations. Negative anomalies occur particu-

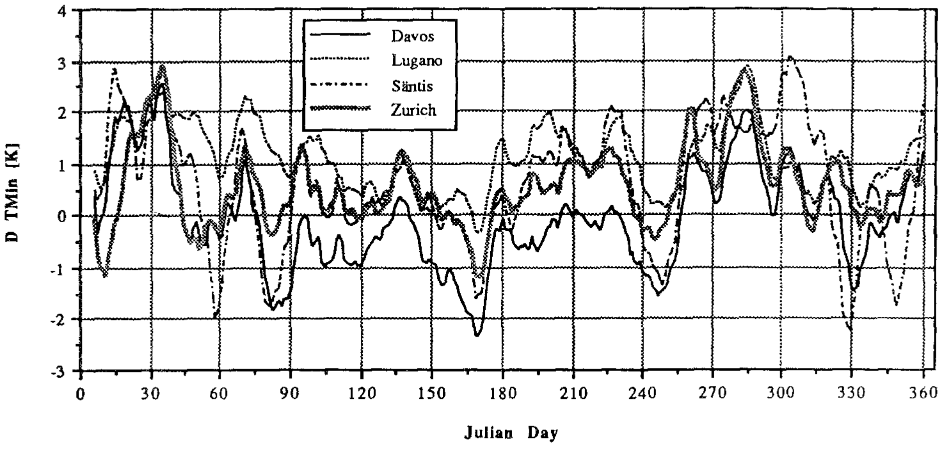

Fig. 18. Difference in the average daily minimum temperatures at all four stations between the 1980s and the 1950s

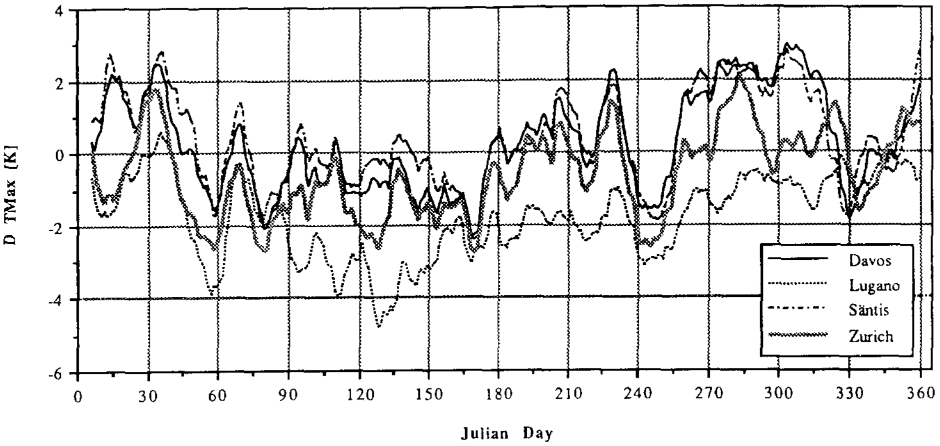

Fig. 19. As Fig. 18, except for average daily maximum temperatures

Table 5. *Correlation Analysis Between the Data Sets Given in Fig. 19*

Correlation between:	R
Zurich – Davos	0.808
Zurich – Lugano	0.683
Zurich – Säntis	0.721
Davos – Säntis	0.944

larly from late winter to mid-summer, but are present at other periods of the year also. The correlation analysis given in Table 5 reflects an essentially similar picture to that of Table 4. The correlation between the two high-elevation stations is remarkable and serves to support the hypothesis that the same climatic change is leading to the same kind of response within the Alps.

4.2 Response of Precipitation

Figure 20 shows the daily precipitation departures from the 1950s to the 1980s. The anomalies exhibit the same kind of periodicity as the temperature data, although the series tends to fluctuate around zero mm for most of the year in Zurich and Davos. The summer months exhibit somewhat negative anomalies which can be explained by the reduction of convective precipitation events resulting from the higher average pressures in the 1980s. There is a sharp transition from negative to positive anomaly at the end of August; a secondary peak of higher precipitation in the 1980s compared to the 1950s occurs towards the end of November and is linked to the reversal of positive pressure anomalies which takes place during this period, i.e., by assuming that on average during the 1980s, the dip in pressures

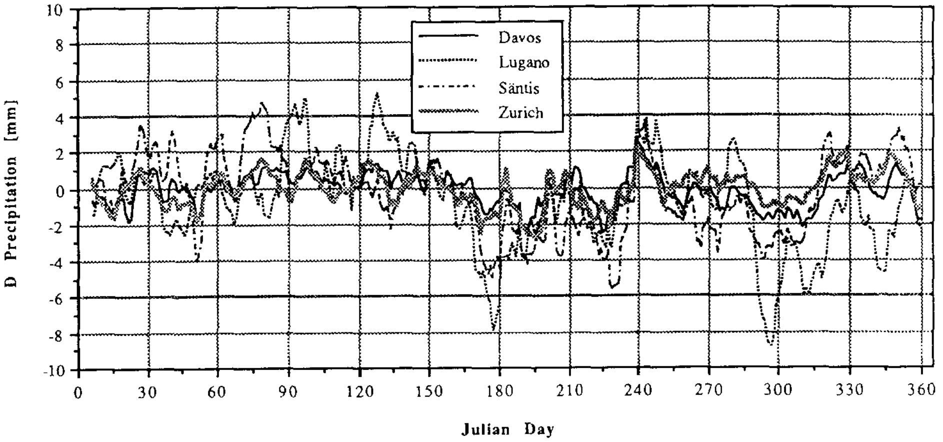

Fig. 20. As Fig. 18, except for average daily precipitation totals

Table 6. *Correlation Analysis Between the Data Sets Given in Fig. 20*

Correlation between:	R
Zurich – Davos	0.670
Zurich – Lugano	0.419
Zurich – Säntis	0.672
Davos – Säntis	0.714

represents the passage of frontal systems and associated precipitation events. However, other sharp pressure transitions, such as at the end of February and fom March to April do not lead to the same precipitation response. As seen in the correlation analysis given in Table 6, Lugano does not exhibit the same behavior in precipitation anomalies. It has by far the greatest amplitude in the series and is often out of phase with the other stations. Late fall is clearly drier in the 1980s while April and May tend to be wetter, a feature which is not as outstanding in the other data. This is once more indicative of the presence of a different climatic régime to the south of the Alps which modulates the influence of the zonal-type synoptic situations and associated blocking highs which were experienced in the 1980s.

It is worth commenting here on the quite remarkable results obtained in Table 6; in a region as complex as the Alps, where the orography may not only amplify or suppress precipitation of frontal or convective origin, but also exhibit strong regional differences according to exposure, slope orientation, and altitude, it is surprising to see that to the north of the Alps, a large fraction of the observed precipitation changes which have occurred between the 1950s and the 1980s can be identified at Zurich, Davos and Säntis. This similarity of precipitation observed at sites which are very different geographically implies that synoptic systems, rather than locally-forced orographic or regional convection, stand out more clearly in the 1980s than in the 1950s as the dominant precipitation mechanism. This is perhaps not surprising for a mid-latitude region, but it is nonetheless interesting to be able to identify the synoptic forcing in records which one could expect to be strongly contaminated by regional and local factors.

4.3 Response of Sunshine Duration Hours

For all stations, the sunshine duration distribution (Fig. 21, for Davos) is characterized by two peaks, a primary one in the 0–5% range (i.e., completely overcast skies) which accounts for 25–30% of the values, and a secondary one in the 90–100% range (completely clear skies). A comparison between the two decades shows that this bimodal distribution is modified; the primary peak undergoes practically no change, whereas at the other end of the range, the shift is either towards higher sunshine duration (as in Davos, Fig. 21; and Säntis), or lower sunshine hours (Zurich and Lugano). The shift in the vicinity of maximum sunshine duration occurs at the expense of minor adjustments to the frequency distribution in the 30–80% range. The difference between the low and high elevation sites is related to the change in the frequency of high pressure episodes, which are accompanied by stratus formation at lower elevations and clear skies in the Alps, as described in the introduction to this section.

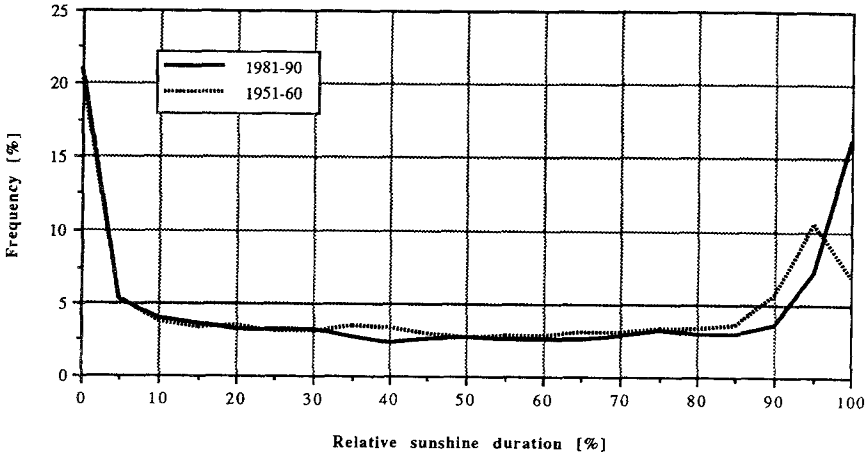

Fig. 21. Difference in the frequency distribution of relative sunshine duration in Davos between the 1980s and 1950s

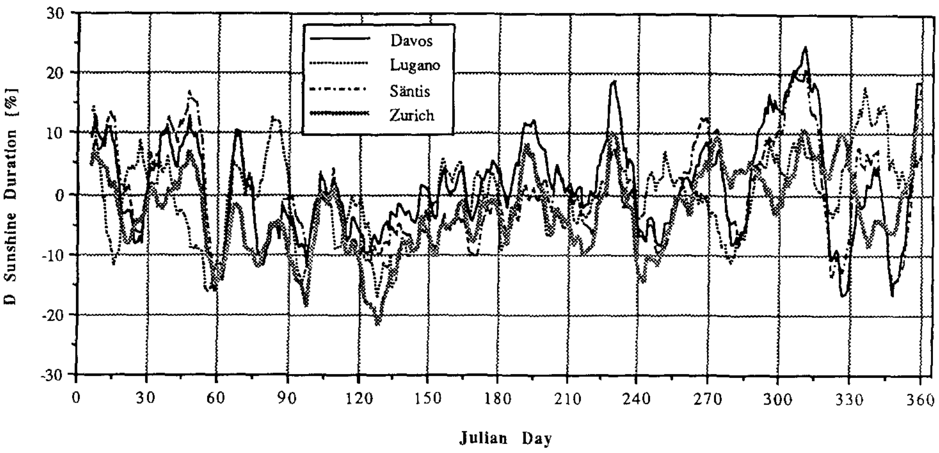

Fig. 22. As Fig. 18, except for average relative sunshine duration

The anomaly of relative sunshine duration between the 1980s and the 1950s at all four stations is given in Fig. 22. The anomaly curve shows that spring is characterized by lower sunshine hours in the 1980s, whereas early fall, winter, and mid-summer (July and August) exhibit higher values. As with the precipitation data, Lugano tends not to follow these patterns; in particular late March and early December show strong positive departures of sunshine duration. This is due to the fact that these are periods in which the likelihood of synoptic disturbances embedded in a westerly airflow crossing Switzerland is high; in such situations, the Alps act as a barrier to the flow and mitigate the effects of such disturbances to the south of the Alpine chain.

Table 7 confirms the fact that the Lugano statistics are different from the other stations, while the two high-altitude stations of Davos and Säntis show remarkable agreement due to the fact that if sunshine is present at one site, it is likely to be present at the other site during periods of extended high-pressures.

4.4 *Response of Snow Cover*

Although it is tempting to use snow as an indicator of climate change, it is a very sensitive variable which can be influenced by a wide range of factors other than simply temperature; for example, snow statistics will be influenced by the amount of snowfall at the onset of the winter season. A small initial quantity of snow is likely to melt quickly in the presence of sunshine, so that until there is more than a critical amount of snow on the ground, there will be little chance of significant accumulation. On the other hand, heavy snowfall at the beginning of the season will lead to longer-lasting snow even in the presence of sunshine or mild temperatures. Because snow amount holds the 'memory' of its initial conditions more than the other climatological variables, it is perhaps less valuable in terms of climate change analysis, and it is not as obvious to repeat here the analysis of differences in snow depth between the 1980s and the 1950s; the entire record for Davos (1931–1992) will therefore be discussed.

Table 7. *Correlation Analysis Between the Data Sets Given in Fig. 22*

Correlation between:	R
Zurich – Davos	0.622
Zurich – Lugano	0.367
Zurich – Säntis	0.608
Davos – Säntis	0.865

In terms of the response of snow depth to the observed climate change, particular features nevertheless stand out; a comparison between Figs. 7 and 14 shows that periods of persistent high pressures, especially towards the end of the 1980s, were accompained by low snow depth. This reflects the fact that snowfall during episodes of blocking high pressures was insufficient to allow snow to accumulate to the depths generally attained in other years of greater snow abundancy.

Figure 23 shows that the beginning of the snow season in Davos (for the 25 cm threshold) underwent a change from the 1930s to the early 1970s

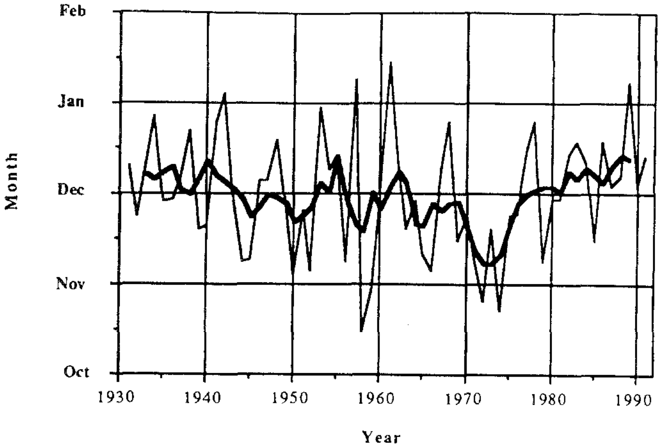

Fig. 23. Evolution of the beginning of the snow season in Davos, 1901–1992; the bold line represents a 5-year filter function to remove high-frequency signals from the data

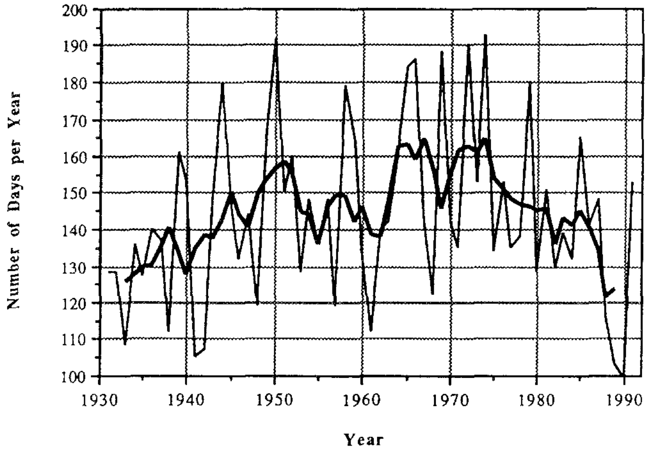

Fig. 24. Evolution of the duration of snow exceeding 25 cm in Davos, 1901–1992; the bold line represents a 5-year filter function to remove high-frequency signals from the data

when the snow appeared as much as one month earlier in the early 1970s compared to the early 1930s; in the last 20 years, however, the beginning of the snow season has reverted to its values at the origin of the time series. In Fig. 24, the duration of snow cover in excess of 25 cm has an inverse relationship, i.e., there was a marked increase in the duration of the snow season from 1930–1970 from less than 130 days with *continuous* snow cover exceeding the selected threshold value to over 160 days in the mid 1960s and early 1970s. The duration of continuous snow cover has reverted to its 1930s values in the 1980s, although the data are considerably biased by the winter of 1989–1990 which was the period of least snow duration of the entire record (only 98 days of continuous snow cover). The aforementioned interannual variability is remarkable in this period, since the winter following 1989–1990 was characterized by over 150 days of continuous snow cover in excess of 25 cm. Similar conclusions can be reached for the beginning of the snow season and the duration of snow for the 50 and 75 cm thresholds. The variability is amplified for the higher threshold values, and for the 75 cm limit, duration varies from 0 to 148 days (average amplitude between 30 and 90 days). The duration of 'deep snow' underwent four major cycles (amplitude approximately 40 days and duration between 8 and 15 years) between 1940 and 1980; on average, duration of 'deep snow' is longer in the 1980s than in the 1930s.

Snow is probably the least reliable climatological parameter, not only because of its strong year-to-year variability in onset, duration, and total depth of snow cover, but also because it is a very regional feature. At equivalent altitudes in other parts of the country, or even at neighboring locations with different geographical aspects (slope orientation and exposure), the situation can be markedly different. An analysis we have made of the snow data for Montana (Canton of Valais) shows that the duration of snow cover has progressively increased from 1930 to the present time.

However, at an altitude barely 100 m lower than Davos, the south-facing resort of Montana experiences between 30 and 50 days less snow cover (at the 25 cm threshold) than Davos.

The conclusions presented here are in agreement with more exhaustive analyses of snow statistics undertaken by Müller and Kappenberger (1991) and Rohrer (1992); these authors have based their analyses on some of the longest existing snow statistics, in particular the Clariden snow field in Central Switzerland.

4.5 Links to Synoptic-Scale Influences

To this point, it has been established that there has been a regional response to changes in two periods of differing climatic régimes, namely the 1980s (characterized by generally high pressures and in phase with the NAO Index) and the 1950s (out of phase with the NAO Index and exhibiting low persistence of high pressures). In this final section, it is shown statistically that the observed anomalies between these two periods are indeed a function of the large-scale forcing associated with changes in the NAO Index.

It was seen in the discussion that the periods of anomalously high pressures occurred essentially from late fall to late winter, and spring and summer months exhibited pressure anomalies of much lower amplitude. The months of January and July have therefore been selected to represent these periods of very high and low pressure anomalies, respectively. Correlations have been established between the pressure anomaly (i.e., the synoptic forcing term) and the variables representative of the regional response (i.e., daily maximum and minimum temperatures, precipitation, and relative sunshine duration), and are illustrated in Figs. 25 and 26 for January and July, respectively.

Relative sunshine duration and precipitation anomalies are particularly well correlated with the pressure anomalies in Davos, Säntis, and

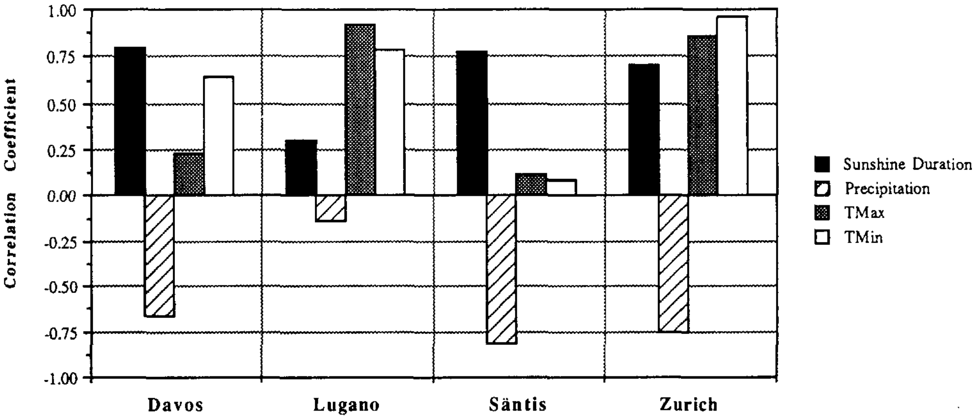

Fig. 25. Correlation between mean January pressure anomalies and other climatological variables

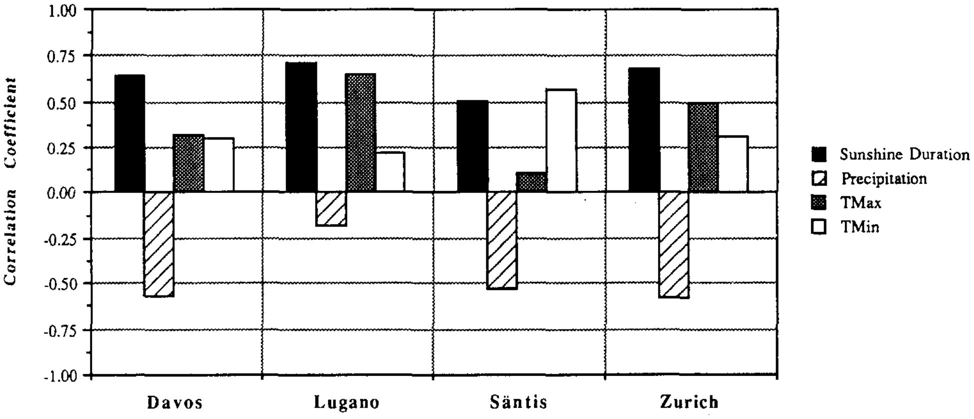

Fig. 26. As Fig. 25, except for July

Zurich, and much less so at Lugano. This indicates that the Lugano records are less influenced by westerly régimes than the other stations, and are more subjected to Mediterranean-type climates; high pressure over the northern part of Switzerland does not necessarily lead to the formation of stratus or fog as is the case in Zurich, so that insolation and precipitation in Lugano are essentially decorrelated from the pressure anomalies.

Correlations between pressure and temperature anomalies are high at Lugano and Zurich, and low at the two high-elevation stations. Temperatures during winter in the mountains can be affected by a number of local factors such as slope orientation and exposure. According to the position of a high-pressure cell, temperatures can either be relatively mild, as in the case of an extension of the Azores High over Europe which would advect mild air at height, or cold as in the case of a high-pressure cell located over Scandinavia, Eastern Europe or Russia, where cold-air advection would be the dominant feature. While the presence of a persistent high-pressure zone leads to a significant increase in sunshine duration, the presence of sunshine is not in itself the unique controling factor on temperature; as a result, high-pressure systems can lead to a wide range of temperature responses at high elevations. A winter high-pressure system influencing Zurich, whether it be of a "warm" Azores-High type of a "cold" Russian or Scandinavian type of anticyclone, will generally be accompanied by persistent stratus formations or, at best, misty conditions which strongly attenuate the incoming solar radiation. Such a situation will essentially modulate the amplitude of diurnal temperature fluctuations; since there is a direct link between the overcast skies and pressure, it is not surprising, therefore, that the relation between pressure and temperature is also high in Zurich.

The high correlation between pressure and temperature anomalies in Lugano can at first sight seem unusual, since Lugano is only partially influenced by Atlantic régimes. A persistent high-pressure system will generally result in relatively mild conditions south of the Alps. A "warm" high pressure system will lead to an influx of mild Mediterranean air to the southern foot of the Alps, while a "cold" system will generate a weak spill-over of air over the Alpine barrier which then warms by adiabatic compression as it descends towards the plains of Lombardy.

In July (Fig. 26), when the pressure anomalies are lower, correlations between this quantity and the anomalies of the other variables are substantially less than in January. This is principally because the atmosphere is much less stable in the summer months, so that a number of regional factors contaminate the data and reduce the overall correlation between the synoptic and the local regional parameters. In particular, July and August are periods in which the probability of convective instability and precipitation is at a maximum. While such instabilities can be triggered by synoptic systems, they remain an inherently regional feature capable of determining the intensity of precipitation and associated temperature changes. From this type of analysis and the available data, it is difficult to dissociate the relative magnitudes of regional features such as convective instability or orographic forcing from the synoptic forcing. As a result, the broad correlation between pressure and the other variables is not as significant as for the January data.

As a final comment on the response of regional climate variables to the pressure anomalies, a close examination of the different figures presented in this section emphasizes the fact that the amplitude of fluctuations is greatest in the fall and winter months, with the possible exception of precipitation. This is also when the pressure fluctuations are at a maximum, and if one were to remove or damp out the anomalies for this period in the year, the amplitude of the response of the regional variables would also be reduced. This would be reflected in annual average trends discussed in the first part of the paper where the rise of temperature in the 1980s, in particular, would have been of a much more modest nature.

5. Conclusions

An analysis has been conducted of the behavior of a number of variables which are representative of regional-scale climatological characteristics in Switzerland, both within the Alps and at low-elevation sites to the north and to the south of the Alpine chain. The data have been extracted from the computerized Swiss Climate Data Base and include daily values of different climate variables from 1901–1992.

The annual trends of temperature are in accord with the global warming tendencies especially in the 1980s, although the regional signal is amplified with respect to the global record. Warming is particularly marked during the nocturnal hours (minimum temperatures), and less pronounced for the maximum temperatures. Precipitation shows no significant trend between the beginning and the end of the record, while sunshine duration is seen to decrease until the early 1980s. Snow exhibits strong interannual variability, but it cannot be stated that there is a marked reduction of snow in the Alps despite an unusual run of three winters at the end of the 1980s and at the beginning of the 1990s with less-than-average snow amounts.

Pressure is considered to be representative of the large-scale climatological fields and is seen to exhibit particularly anomalous behavior in the 1980s through a dramatic rise in the frequency and persistence of blocking highs over Switzerland. The behavior of pressure is closely associated to the North Atlantic Oscillation Index for at least two twenty-year periods of this century, confirming that a link does indeed exist between the synoptic and the regional scales. The significant correlation with the North Atlantic Oscillation Index coincides in the 1980s with extended periods of blocking high events.

The sensitivity of temperature, precipitation, sunshine duration, and snow depth to changes in large-scale climatological régimes has been demonstrated by comparing two periods in which blocking episodes are persistent and frequent (i.e., the 1980s) and where blocking is practically nonexistant (i.e., the 1950s). These two decades represent two distinct synoptic régimes, and it is of interest to observe that the regional climate responds in a similar and coherent manner at all stations despite the obvious differences in site location, orientation, and location. Differences in the local climate of Lugano, south of the Alps, can be explained by the presence of the mountains themselves, which act as a significant barrier to many of the perturbations embedded in a zonal flow and which affect mainly the north of the Alps; Lugano is probably affected as much by the influence of the Mediterranean climate régime as by the Atlantic régime.

There is some evidence in the data analyzed throughout this paper that climate trends in Switzerland are consistent with global warming tendencies; indeed, some of the signals seem to be amplified. It is not possible, however, to impute the observed regional changes to changes in atmospheric greenhouse-gas concentrations (unless it can be demonstrated that the changes in the North Atlantic Oscillation Index are themselves a direct consequence of greenhouse-gas increases). If such a conclusion were to be drawn in future on the basis of ongoing coupled ocean-atmosphere modelling experiments, then the quantification of the response of regional climate characteristics to synoptic forcing undertaken in this paper would help improve the understanding of the relationship between global climate change and regional climate response.

Acknowledgements

The authors would like to thank Prof. A. Ohmura and Dr. M. Rotach of ETH-Zurich for their useful comments regarding the scientific content of this paper. The authors would also like to thank Drs. Bantle and Gisler from the Swiss Meteorological Agency in Zurich for their kind help and advice on the use and interpretation of the Swiss Climate Data Base. This work has been partially supported by the Swiss National Science Foundation under Grant Numbers 4031-33250 and 4031-38271.

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