VARIATIONS OF SNOW DEPTH AND DURATION IN THE SWISS ALPS OVER THE LAST 50 YEARS: LINKS TO CHANGES IN LARGE-SCALE CLIMATIC FORCINGS

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Abstract. A study of snow statistics over the past 50 years at several climatological stations in the Swiss Alps has highlighted periods in which snow was either abundant or not. Periods with relative low snow amounts and duration are closely linked to the presence of persistent high surface pressure fields over the Alpine region during late Fall and in Winter. These high pressure episodes are accompanied by large positive temperature anomalies and low precipitation, both of which are unfavorable for snow accumulation during the Winter. The fluctuations of seasonal to annual pressure in the Alpine region is strongly correlated with anomalies of the North Atlantic Oscillation index, which is a measure of the strength of the westerly flow over the Atlantic. This implies that large-scale forcing, and not local or regional factors, plays a dominant role in controling the timing and amount of snow in the Alps, as evidenced by the abundance or dearth of snow over several consecutive years. Furthermore, since the mid-1980s, the length of the snow season and snow amount have substantially decreased, as a result of pressure fields over the Alps which have been far higher and more persistent than at any other time this century. A detailed analysis of a number of additional Alpine stations for the last 15 years shows that the sensitivity of the snow-pack to climatic fluctuations diminishes above 1750 m. In the current debate on anthropogenically-induced climatic change, this altitude is consistent with other studies and estimates of snow-pack sensitivity to past and projected future global warming.

1. Introduction

Snow cover and duration play a key role in a number of environmental and socio-economic systems in mountain regions. The behavior of hydrological systems and mountain glaciers is closely linked to the timing and volume of snowfall and snow melt (Barry, 1990). In a country such as Switzerland, where 60% of the electricity production is from hydro-power, energy supply is highly dependent on, and sensitive to, changes in snow amount and duration. Mountain ecosystems, particularly vegetation in high Alpine regions, also depend on snow cover to protect numerous species from frost damage during the Winter months. The economic value of snow in most Alpine countries is paramount for Winter tourism; many small ski resorts in Switzerland have faced severe shortfalls in earnings whenever snow has been sparse or absent during major vacation periods, particularly at Christmas and over the February school recess (Abegg et al., 1994).

As an indicator of climatic change, snow is an interesting variable, because it is dependent not only on temperature but also on precipitation. Unlike most meteorological variables taken individually, records of snow depth, spatial extent and

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duration are not only a function of diurnal values of temperature and precipitation, but are also based on the history of these variables over a period prior to the observation itself. As a result, the interpretation of ‘instantaneous’ snow statistics is far from trivial because a given value of snow depth recorded on a particular day will generally have little relation to the temperature observed on that same day. Over longer periods, however, snow-pack records averaged over monthly or yearly periods provide a useful insight into interannual or longer time-scale climatic fluctuations, since the day-to-day precipitation events and temperature fluctuations are smoothed out, allowing the longer-term fluctuations of snow amount to be analyzed.

There has been much concern expressed in recent years that the run of mild winters with relatively little snow in the Alps (particularly during the critical vacation periods) in the latter part of the 1980s and the early 1990s may already be a sign of the anthropogenic signal on climate change. The relative lack of snow, particularly at low elevations, has been unusual; Pfister (1994, personal communication) has stated that on the basis of historical records, the conditions experienced at the end of the 1980s have never been observed in the last 700 years. Baumgartner and Apfl (1994) have indicated that Alpine snow cover reached its smallest extent during the 1980s; this in turn had significant impacts on economic activities in the Alps, particularly tourism (Price, 1994).

Föhn (1991) has shown that while the lack of snow at the end of the 1980s was unusual, the phenomenon was most marked at low to medium elevation sites. At high elevations, little difference in snow depth and duration have been observed with respect to the long- term mean at the Weissfluhjoch site (2540 m above sea level) in the eastern Swiss Alps. This is related to the fact that snow which accumulates in the early part of the season will be less sensitive to warm periods during the Winter at higher elevations, i.e., once the snow has fallen, it will remain on the ground, albeit with losses through evaporation and sublimation processes. This is not the case at lower elevations, which can be subject to extended periods of temperatures above the freezing point.

In view of the importance of snow as a controlling factor on a number of environmental and economic systems in mountain regions, and as an indicator of climatic change on annual to decadal time scales, this paper will focus on snow statistics in the Swiss Alps over a 50-year period from 1945–1994 inclusive. Snow records from stations located at different altitudes have been selected to emphasize not only the altitudinal relationship of snow depth and duration (Slatyer et al., 1984; Witmer et al., 1986), but also the relative synchroneity of response of snow depth and duration to well-defined changes in large-scale climatic forcings during this period. An additional focus will be to investigate snow data from a total of 12 stations for the period 1980–1994, which encompass the unusually mild winters of the late 1980s, in order to highlight whether there are critical altitudes above which the vulnerability of snow amount to climatic change is reduced. Such estimates can

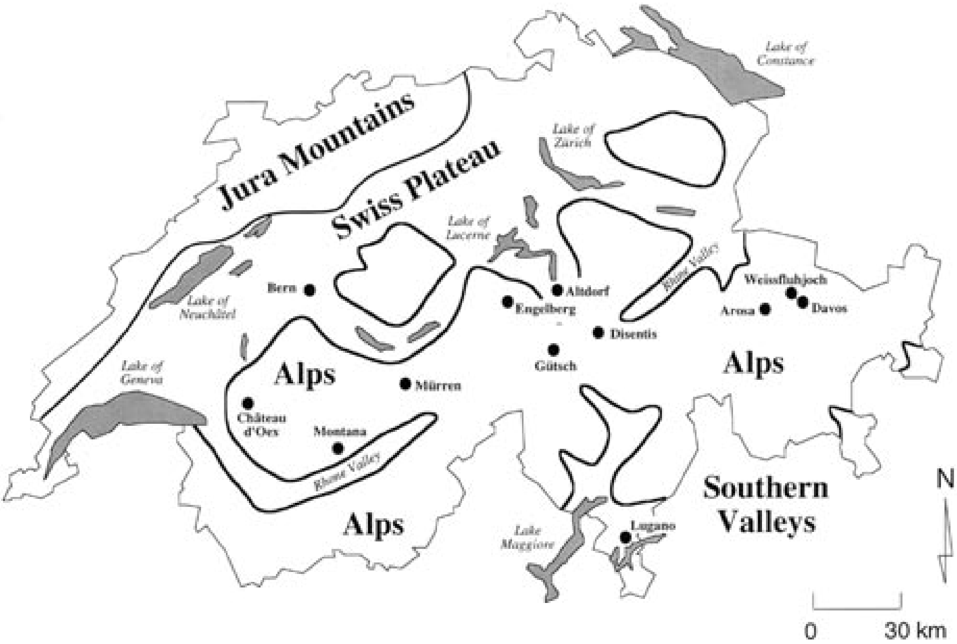

Figure 1. Map of Switzerland indicating the locations of the 12 climatological sites analyzed in this study.

be of use for determining the likely response of mountain snow characteristics to future global warming as projected by the IPCC (1990, 1995).

2. Analysis of 50 Years of Snow Statistics

2.1. SNOW DEPTH AND DURATION

Figure 1 illustrates the location in Switzerland of the three principal stations which have been investigated for the 50-year period, and the additional 9 stations used for the focus on the 15 years from 1980 to 1994. These stations, listed in Table I, have been selected on the basis of their geographical and altitudinal representativity, and the availability of daily climatological statistics for the period chosen.

Snow depth in the Swiss observational network is recorded on the basis of the thickness of snow cover measured each day, regardless of water content. Figure 2 provides an overview of the year-to-year changes in the duration* of snow cover for a threshold value of 10 cm at the three principal stations; a five-year smoothing function has been applied to the data in order to remove the noisiness associated with interannual fluctuations. There appears to be a decadal-scale variability associated

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* Snow duration for a particular depth threshold is defined as the percentage of time over which that threshold is exceeded with respect to the maximum possible duration, i.e., one year or one month.

Table I

Swiss climatological stations used in this study, in increasing order of altitude

Name	Altitude [m]	Period considered
Lugano	276	1980–1994
Altdorf	451	1980–1994
Bern	570	1980–1994
Château d’Oex	960	1945–1994
Engelberg	1018	1980–1994
Disentis	1180	1980–1994
Montana	1495	1945–1994
Davos	1590	1945–1994
Mürren	1639	1980–1994
Arosa	1847	1980–1994
Gütsch	2288	1980–1994
Weissfluhjoch	2540	1980–1994

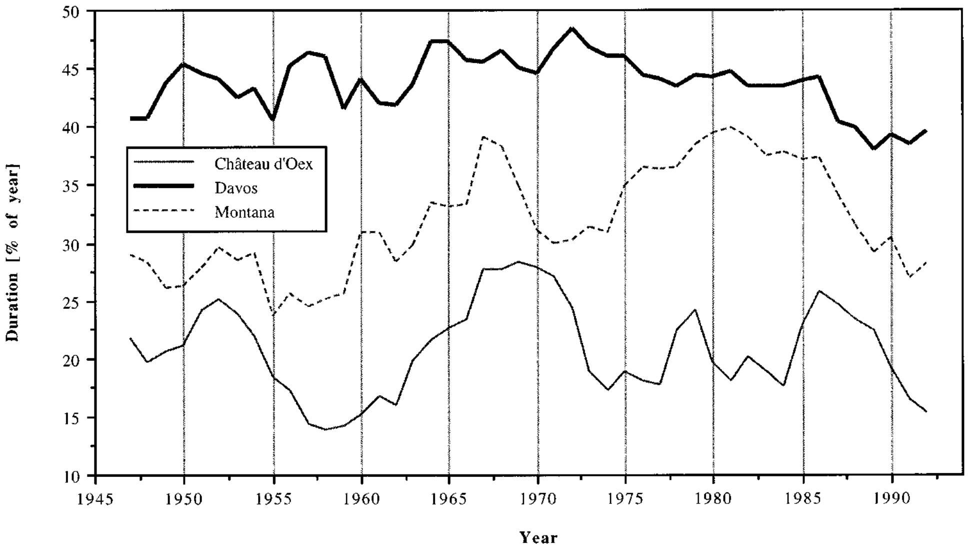

Figure 2. Annual average duration of snow cover in Château d’Oex, Davos, and Montana from 1945–1994 for a snow-depth threshold of 10 cm.

with the snow duration records, particularly at Château d’Oex and Montana, with a marked decrease since the mid-1980s at all sites. These reach their lowest values for the last 40 years at Château d’Oex and Montana, and for the entire record at Davos in the 1990s. The fluctuations between ‘long’ and ‘short’ winters represents a difference of up to 45 days per year in terms of snow cover.

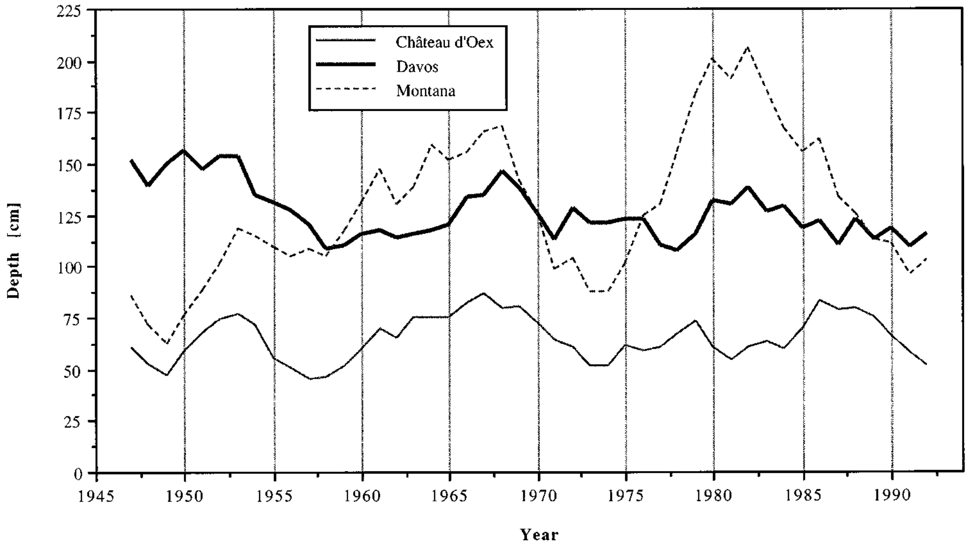

Figure 3. As Figure 2, except for maximum snow depth.

Figure 3 shows the maximum snow depth recorded each winter at the three stations during the 50-year period. Again, the very noisy interannual variability has been removed from the time-series, thereby serving to highlight the decadal-scale fluctuations. It is seen from Figures 2 and 3 that there exists a relatively good correspondance between snow depth and snow duration, i.e., long winters will tend to be associated with deep snow cover, not only because the accumulation period is longer but also because precipitation tends to be more intense, as has been pointed out by Rebetez (1996). Simple linear regression fits for all curves in both figures show no significant trends since 1945; in the absence of the reductions in snow duration and snow depth which have intervened since about 1985, there would in fact have been a slight increase in both duration and maximum depth at these sites.

Montana exhibits the greatest range of fluctuations in snow duration and snow depth; its south-facing situation makes it sensitive to extremes of either sunshine during high pressure episodes, or abundant snowfall during meridional synoptic flow situations which the other mountain stations are less subject to. During these 50 years, Montana exhibits two distinct periods of snow abundance, namely the mid 1960s and the early 1980s.

Large fluctuations in snow amount and duration from one year to the next, or over a period of several years, are largely accounted for by anomalies in seasonal temperature and precipitation; for the stations illustrated here, up to 80% of the variance in snow cover and duration can be explained by departures of temperature and precipitation from their long-term means. Years with relatively little snow are associated with large positive temperature and negative precipitation anomalies, which are closely related to the strength of the North Atlantic Oscillation index, as will be discussed in a later section. The interdependency between temperature and precipitation is highly complex in the Alpine region, and is a function of altitude and site. Rebetez (1996) has shown that above an elevation of about 1000 m, warm winters tend to be drier than the norm, with the reverse being true. The temperature-precipitation relationships at lower elevations are complicated in winter by the presence of fog or stratus, particularly during persistant high pressure episodes. The upper limit of the stratus is in the range of 800–1000 m; below this altitude range, temperatures can be seasonally or even anomalously cold, while above the fog, they tend to be anomalously warm. Precipitation both above and below the stratus is well below average under anticyclonic conditions, so that correlations between precipitation and temperature can be substantially different according to the altitude, and may even change sign between sites located above or below the stratus layer.

In a study of regional climate change in Switzerland over this century, Beniston et al. (1994) have shown that in terms of seasonal anomalies, both minimum and maximum temperatures have in recent years exhibited marked positive departures in the early fall and throughout the winter. Precipitation also shows significant negative anomalies in the fall, which have been on the increase since the mid-1980s. The combination of precipitation deficits and above-normal temperatures during the early part of the snow season thereby impacts heavily upon snow depth and duration for the rest of the season. Even if snow falls later in the season, the fact that temperatures tend to be above normal in winter will also contribute to reducing the duration and depth of the snow cover. It can therefore be concluded that, while both appropriate temperature and precipitation conditions are pre-requisites for snow to fall and remain on the surface, temperature becomes the controling factor once snow is present.

While the latter part of the 1980s received much media and public attention because of the economic consequences of the lack of snow during those winters, the data presented here show that there have been periods in the record where snow depth or duration were as low as during the 1980s. Records prior to 1945, not illustrated here, indicate that many mountain stations experienced sparse snow conditions in the 1930s (e.g., Beniston et al., 1994). These events went relatively unnoticed because at that time the ski industry was only a minor income earner for mountain communities. In the 1960s, however, ski resorts were investing heavily in infrastructure at a time when snow was relatively abundant, so that changes relative to the 1960s baseline are the ones which have generated most of the economic adversity for these resorts and raised public concern as to a possible sign of global warming (Rebetez, 1996).

2.2. LINKS TO LARGE-SCALE SHIFTS IN CLIMATE

The snow statistics illustrated in Figures 2 and 3 reflect the shift in climate over the past 50 years and which has been reported more extensively in Beniston et al.

(1994) and others (e.g., Wanner, 1994). Shifts in synoptic-scale forcings, linked to fluctuations of the North Atlantic Oscillation index (NAO*), have been shown to strongly influence the surface pressure field in the Alpine region. In the early 1970s, and since the middle of the 1980s, the wintertime NAO index has been positive, indicative of enhanced westerly flow over the North Atlantic. Such flow has in recent decades been associated with abundant precipitation over Norway as cyclonic tracks enter Europe relatively far to the north of the continent (Hurrell, 1995). Over the Alpine region, on the other hand, positive NAO indices generally trigger persistent periods of high pressure, in particular during the winter months. The response of the pressure field in the Alps in latter years has been to amplify the signal generated by the NAO index; in the latter part of the record, with increasingly positive NAO indices since 1980, pressure has been on average higher than at any time this century. Beniston et al. (1994) have shown that close to 25% of pressure episodes exceeding the 965 hPa threshold in Zürich (approximately 1030 hPa reduced sea-level pressure) this century occured in the period from 1980–1992, with the four successive years from 1989–1992 accounting for 16% of this century's persistent high pressure in the region. This has not always been the case, however, and blocking episodes over Western Europe have occured during periods where the NAO index was below average (Moses et al., 1987); this was also pointed out by Beniston et al. (1994), who noted that strong positive NAO indices can result from either a deepening of the Icelandic Low or a strengthening of the Azores High; the fact that the index can comprise both subpolar and subtropical pressure fluctuations explains why the correlation between the Zürich pressure field and the NAO index is not always as high as it has been since the 1970s. Additionally, it should be emphasized that pressure in Zürich is considered representative of the pressure field over Switzerland, i.e., when averaged over periods of a month to a year, any local differences in pressure between one region another another (e.g., during the passage of a synoptic disturbance) are smoothed out. This implies that a high surface pressure measured in Zürich is indicative of the presence of a large-scale anticyclonic field over Europe and the Alps.

Figure 4 shows the wintertime (DJF: December, January and February mean) anomaly of the pressure field in Zürich compared to the DJF anomaly of the NAO index over the same period. The correlation between the two curves is positive and particularly high for the periods 1930–1950 and 1970–present. The amplification of the pressure signal in Switzerland has been particularly marked and systematic since 1980; at no time in the last 15 years has the average annual pressure reverted to its long-term average value. More details on the correspondance between these two curves are discussed by Beniston et al. (1994).

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[*] The NAO index is computed on the basis of the pressure difference between Stykkisholmur, Iceland and Lisbon, Portugal. The index is a measure of the strength of westerly flow over the Atlantic. The data set has been kindly provided by Dr. James W. Hurrell of the National Center for Atmospheric Research in Boulder, Colorado.

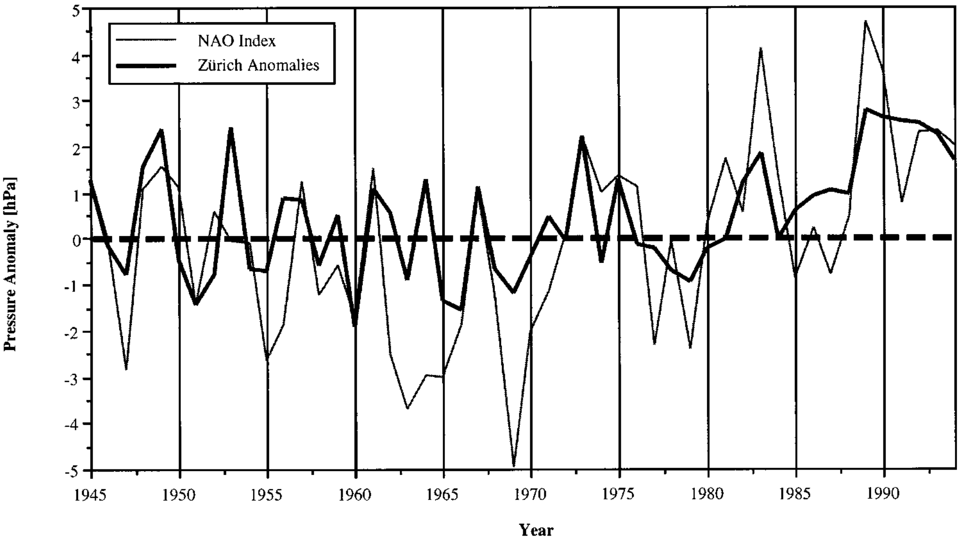

Figure 4. Time series of the North Atlantic Oscillation index and surface pressure in Zürich.

Observed episodes of persistent high pressure in Switzerland, sometimes associated with blocking in the formal sense of the term, are most often accompanied by large positive departures of temperature; they are also linked to extended periods of low or negligible precipitation. These two factors taken together, as the main controls on snow, explain much of the observed sparseness during times of positive NAO indices.

Figure 5 illustrates the relationship between average annual snow duration for various depth thresholds at the three climatological sites (which have been smoothed using a five-point filter for the sake of clarity) and the smoothed average wintertime (DJF: December, January and February mean) pressure field as measured in Zürich for the 50-year period. Different snow duration thresholds have been chosen to illustrate the correspondance between shifts in snow duration with shifts in surface pressure. The figure highlights two periods during the record when average pressures increased and peaks exceeded the 1951–1980 climatological mean value, i.e., from 1967–1975 and since 1980. The latter period of the record has been the longest this century where pressure has remained largely above the 30-year climatological average.

It is seen that whenever pressures rise, the snow-pack responds by decreasing in duration (and depth, not shown here). This is particularly visible since 1982 in Davos and Montana, already to some extent for the 50-cm threshold (particularly since 1980) but more so for snow-depth thresholds exceeding 100 cm. For example, with the strengthening of the wintertime mean surface pressure field in the 1980s, periods with 150 cm of snow or more at Davos have all but disappeared since 1985 and at Montana since 1990. There have been other extended periods where snow

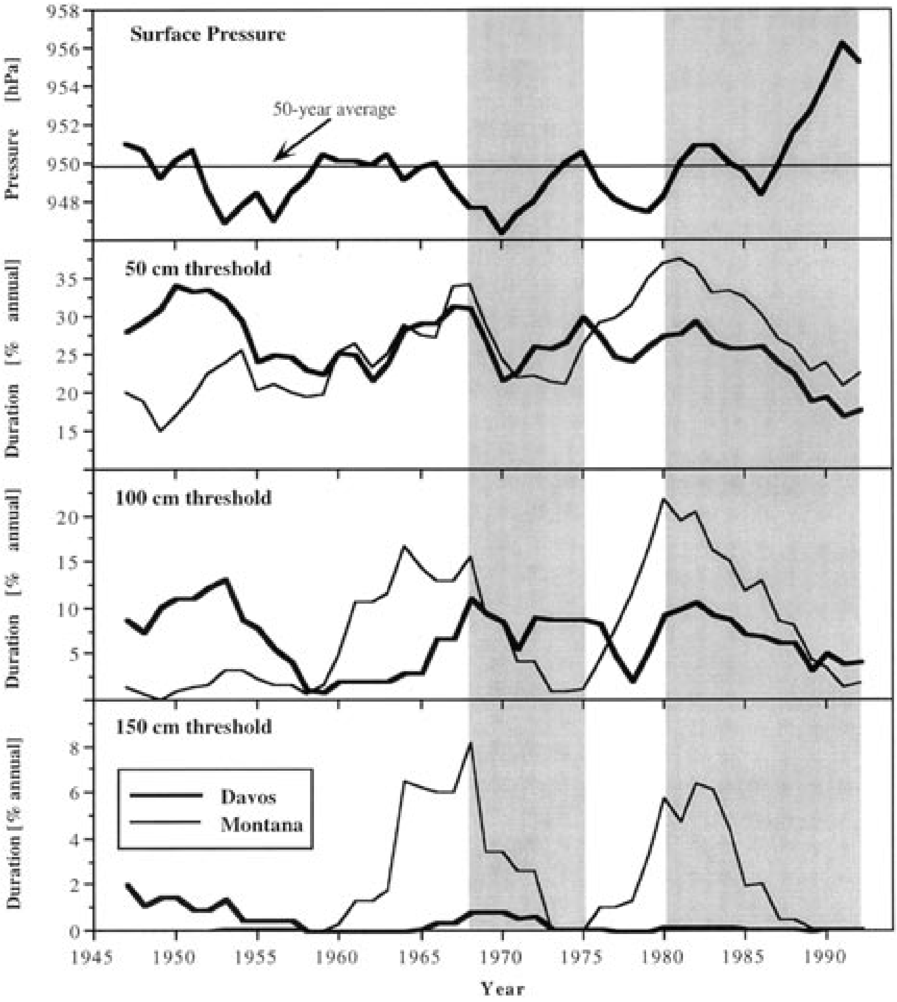

Figure 5. Time series of surface pressure in Zürich and snow duration (as a % of one year) at Davos and Montana for 50, 100, and 150 cm snow-depth thresholds. Gray shading depicts periods of particular correspondence between increases in pressure and reductions in snow duration.

does not exceed this threshold in Davos, as in the 1960s or the late 1970s, where snow amount seems to have had difficulty in recovering from previous years of high wintertime pressures.

There are periods when snow has been abundant in Montana, however, indicative of synoptic precipitation patterns embedded in meridional flows which are favorable to snowfall on the exposed slopes of Montana, as opposed to the more sheltered Davos site.

2.3. MONTHLY SNOW DISTRIBUTIONS OVER 50 YEARS

While annual statistics of snow depth and duration offer some insight into changes in snow-pack linked to shifts in climatic forcings, higher temporal resolution is useful for evaluating the sensitivity of particular periods of the snow season and how these respond to large-scale influences. The foregone discussion which focused on annual statistics have linked snow depth and duration to large-scale climatic forcings via the NAO index and the regional response of surface pressure in Switzerland. It is now of interest to break down the statistics into monthly means in order to investigate whether there is a consistency between what is observed at the interannual scale and at the intra-annual scales.

Figure 6 illustrates the patterns of pressure anomaly fluctuations from the 1951–1980 mean since 1945 for each month of each year. The isolines given in this figure depict clearly the fact, already reported by Beniston et al. (1994), that positive pressure anomalies are greatest in the Winter season. The large positive pressure departures, exceeding 15 hPa in the late 1980s and early 1990s is coincident with the anomalously warm winters and sparsity of snow observed during that period, as previously seen in Figures 2 and 3. Similarly, low snow amounts recorded in the individual winters of 1963/1964 and 1974/1975 can be attributed to the positive wintertime pressure anomalies observed in this figure. What is most remarkable in the 1980s, however, compared to other anomalously warm and snow-sparse periods is not only the very large pressure departures from their average values, but also the fact that these positive anomalies begin very early in the season, i.e., in late September and October. This implies that snowfall was reduced at the very beginning of the season because of persistent high pressure, and whatever little snow subsequently fell during the rest of the season had difficulty in remaining because of the anomalously high temperatures generated by subsiding air in the anticyclone. In 1993 and 1994, Fall pressures were slightly below average, allowing frontal systems to move through the Alpine area and enabling early accumulation of snow. This, combined with the reduction of the magnitude of the Winter high pressure anomaly since 1993, resulted in increased snow amounts and duration, particularly in Montana.

When examining the period from 1973–1983, it is seen that pressures in the Fall were frequently significantly below the 30-year average value; early snowfall and accumulation was more likely to occur under such circumstances. If pressure anomalies remain low during the Winter, as between 1977 and 1982, then snow amount and duration react positively. Any positive pressure fluctuation intervening in the Winter, on the other hand, will tend to negate the accumulation of snow which occurs earlier in the season; one such example is the Winter of 1974/1975, in which a positive anomaly ‘cell’ developed, leading to sparsity of snow during the main part of the season, despite the fact that snowfall occured during the previous Fall. Figure 6 therefore emphasizes the fact that pressure anomalies act as a ‘switch’ which enables or inhibits snowfall and accumulation. When significant

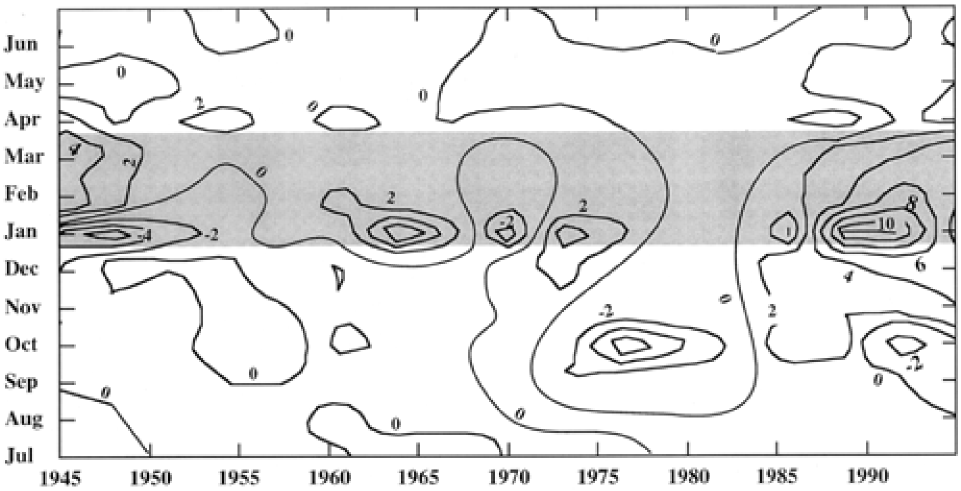

Figure 6. Annual distribution of monthly-mean pressure in Zürich for the period 1945–1994. Gray shading indicates the winter period.

low pressure ‘corridors’ occur in the time diagram, as from 1977–1982, abundant snowfalls are recorded; the reverse is true when positive pressure anomalies lead to shifts in the timing of the beginning of snow-pack accumulation and the triggering of snow-melt at the end of the season. Because these pressure anomalies are linked to the fluctuations of the NAO index, they are not isolated events but generally span a number of years. Large-scale forcing is therefore, on the long term, the dominant control on snow abundance in the Alps; local or regional factors, such as site characteristics (valley or slope location, exposure, orientation, etc.) may determine differences in snow amount at equivalent altitudes (i.e., the statistical noise characterizing interannual variability), but will not influence the timing of the beginning of the snow season and the accumulation of the snow-pack over the Winter period.

Figure 7 shows the distribution of snow duration for the 50-cm snow-depth threshold in Montana. Periods of relative snow abundance, as in the late 1960s and the early 1980s are clearly emphasized in the diagram and are closely linked to the pressure patterns given in Figure 6. The marked decrease in snow duration from 1988–1990 is a particularly striking, although not unique, feature of the record; the late 1940s had significantly less snow and the trend towards durations exceeding 50% were not encountered until the late 1950s. Even the 1988–1992 episode did not see snow duration for the 50-cm threshold go below 50% of maximum possible duration; compared to the years prior to this, where duration reached close to 90%, the decrease was perceived more accutely than the more systematic low snow amounts in the 1940s and 1950s, because of the economic significance snow had gained in the meantime.

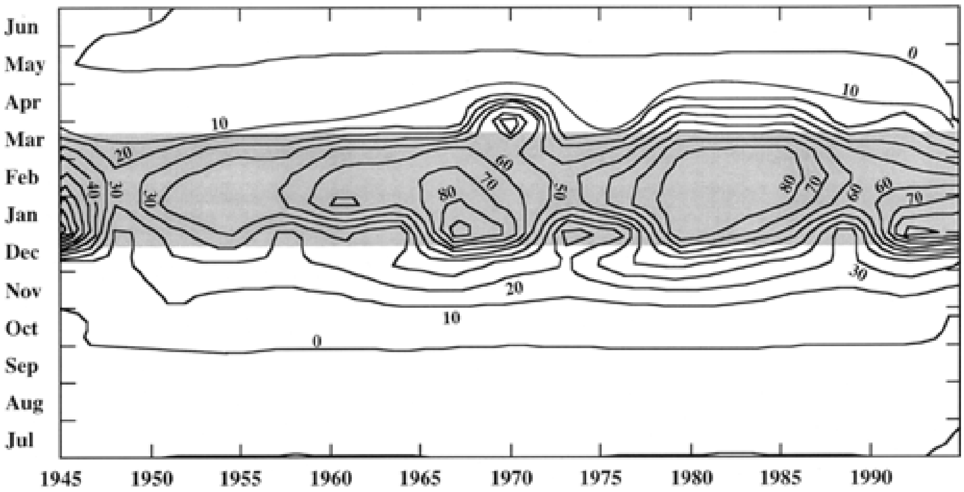

Figure 7. Annual distribution of monthly-mean duration of snow (in % of maximum possible duration) in Montana during the period 1945–1994 for a snow-depth threshold of 50 cm.

What has changed in the late 1980s, however, is the length of the snow season. Since 1988, the periods in which there is more than 50 cm of snow for at least 10% of the time has diminished by up to two months, a situation which has not been encountered since the late 1940s. The decrease at the 0% interface (i.e., when there is just that particular amount of snow on the ground) has decreased by one month in the Fall and close to two months in the Spring. The snow season in recent years has begun on average in late October and ended in late March, whereas one decade ago, the respective timings were early October and late May.

The snow-depth statistics in Château d’Oex given in Figure 8 show that snow depths since the late 1980s are systematically lower than at any other time in the record. This confirms the conclusions for the Montana statistics and additionally illustrates the enhanced sensitivity of lower-elevation sites to mild Winter conditions.

3. Analysis of Snow Statistics for the Period 1980–1994

Because the 1980s were anomalous in a number of ways both in the Alps (two of the coldest winters this century in 1985 and 1987 and four of the warmest in the late 1980s and early 1990s), and globally (6 of the warmest years this century occured during this period as reported by Bradley and Jones, 1992), it is of interest here to determine the sensitivity of snow at different altitudes to the climatological events which took place during this period. In particular, it is of interest to determine whether there are altitudes above which the snow-pack is relatively insensitive to changes in large-scale climatic forcings.

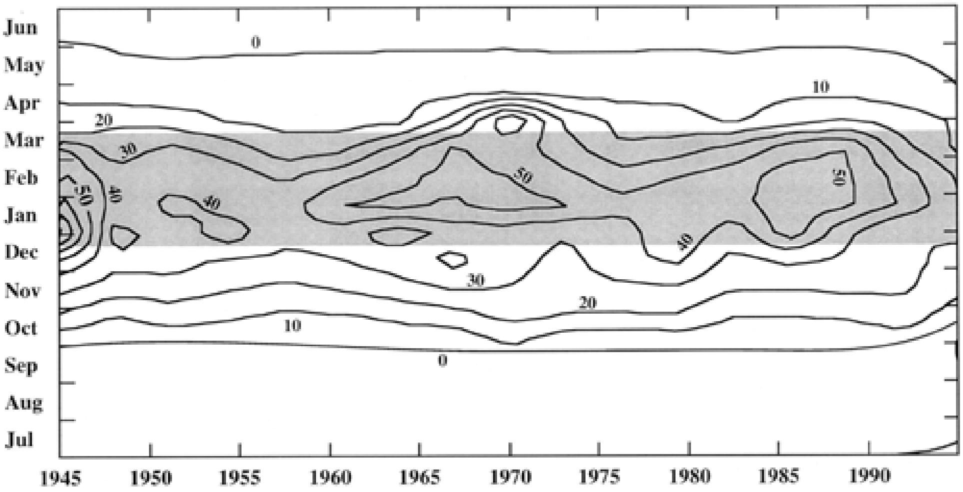

Figure 8. As Figure 7, except for maximum snow depth in Château d'Oex.

Because for monthly averages, large-scale climatic forcing dominates over regional differences in determining snow-pack characteristics, it is possible to analyze the altitudinal behavior of snow even though climatological sites are located in different parts of the Swiss Alps. The discussion will focus here on 9 stations in addition to the three main stations analyzed in the previous section. The full set of stations is illustrated in Figure 1 and listed in Table I; the altitudes of the stations range from 276 m in Lugano to 2540 m at the Weissfluhjoch.

Figure 9 provides an overview of the trends in maximum annual snow depth from 1980 to 1994 for the altitude range represented by the 16 stations. Periods of snow abundance in the early part of the 1980s, particularly at low to medium elevations, gave way to low snow amounts after 1987; these episodes have already been explained by the persistence of very high pressures during these winters. In the early 1980s, sites around the 1000 m level experienced over 140 cm of snow, whereas since 1989 have not encountered more than 50–60 cm of snow. The very anomalous winters of 1988–1990 are seen as a systematic upward shift of the isolines of maximum snow depth to levels between 1750 and 2000 m. This period also saw reductions in snow amount above 2000 m, but in lesser proportions to those at lower elevations. It is clear that if early snowfalls occur in the Fall, accumulated snow is likely to persist throughout the Winter even with little intervening snowfall episodes. The lower elevations, on the other hand, will be much more sensitive to anomalously warm and dry conditions. This situation is further exacerbated by the fact that during warm anomalous periods, temperature anomalies during this period have tended to increase with height, as demonstrated by Beniston and Rebetez (1995). This means that in a situation of persistent high pressures, accompanied by positive temperature departures from the mean, the temperature signal will be amplified with height. A medium-altitude site which could retain its

Table II
Snow-depth correlations between the 12 stations used in this study

	Lugano	Altdorf	Bern	Ch. d'Oex	Engelbg	Disentis	Montana	Davos	Mürren	Arosa	Gütsch
Altdorf	0.72										
Bern	0.86	0.94									
Ch. d'Oex	–0.03	0.47	0.61								
Engelbg	0.18	0.72	0.66	0.83							
Disentis	0.50	0.59	0.58	0.03	0.73						
Montana	–0.34	0.07	–0.11	0.39	0.63	0.45					
Davos	0.17	0.53	0.35	0.15	0.68	0.87	0.69				
Mürren	–0.35	0.06	–0.06	0.40	0.65	0.52	0.92	0.65			
Arosa	–0.10	0.24	0.11	0.08	0.38	0.80	0.72	0.89	0.82		
Gütsch	–0.21	0.13	–0.02	0.26	0.65	0.65	0.96	0.81	0.93	0.86	
Weissfl.	–0.40	0.14	–0.14	0.17	0.48	0.48	0.82	0.81	0.79	0.85	0.84

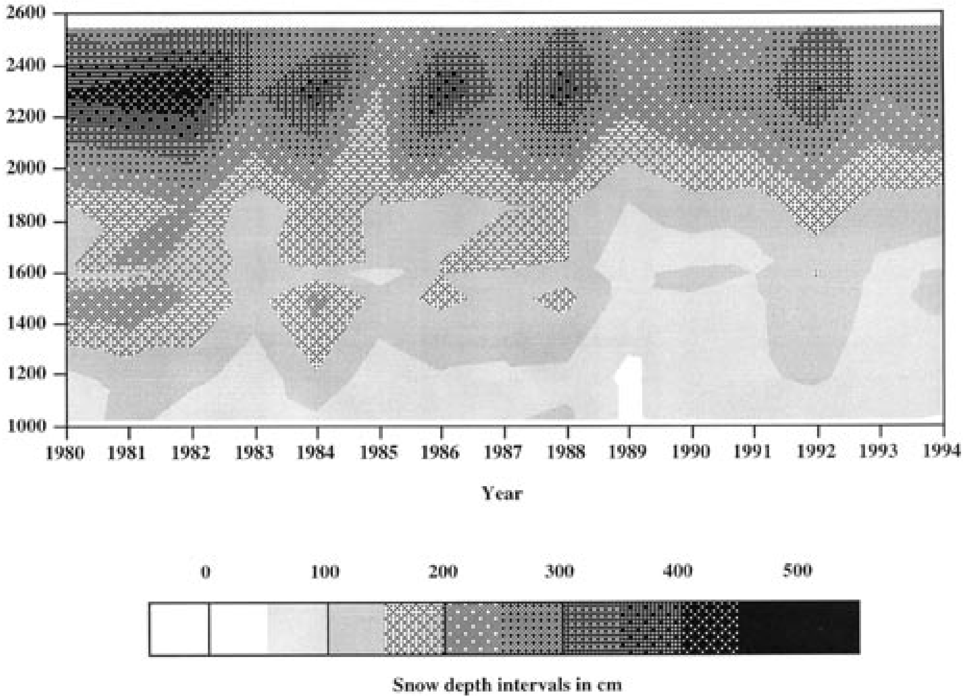

Figure 9. Altitudinal distribution of maximum snow depth for the period 1980–1994, based on snow statistics from 9 of the Alpine stations located above 1000 m above sea level (see Table I).

snow-pack if the temperature gradient were adiabatic in fact may lose snow mass because of this amplification phenomenon. The larger temperature anomalies with height push the freezing point to higher elevations than would be expected in an adiabatic atmosphere. Beniston and Rebetez (1995) showed that during the warm winters between 1988 and 1992, temperature anomalies averaged about 0.5 K at 500 m height in the Alps and over 3.0 K at 2500 m. While this latter figure would be unlikely to raise the isotherm above the freezing point, snow sensitivity to temperature anomalies has been greatest in the intermediate altitudinal range, i.e., between 1200 and 1800 m. Since 1993, with the reduction in the persistence of wintertime high pressures, there has been an increase in snow amount at levels above 1400 m; altitudes below that have not reverted to the snow conditions which they experienced in the first half of the 1980s because of persistently mild Winter temperatures.

In order to further investigate the most sensitive altitudinal range to mild Winter conditions since 1980, the distribution of relative variability of snow duration with height has been analyzed for a number of different thresholds. Relative variability is defined as the standard deviation of a quantity normalized by its mean value; its application is often useful for precipitation statistics, including snowfall and snow amount, because of the high altitudinal dependency of both the variance and the

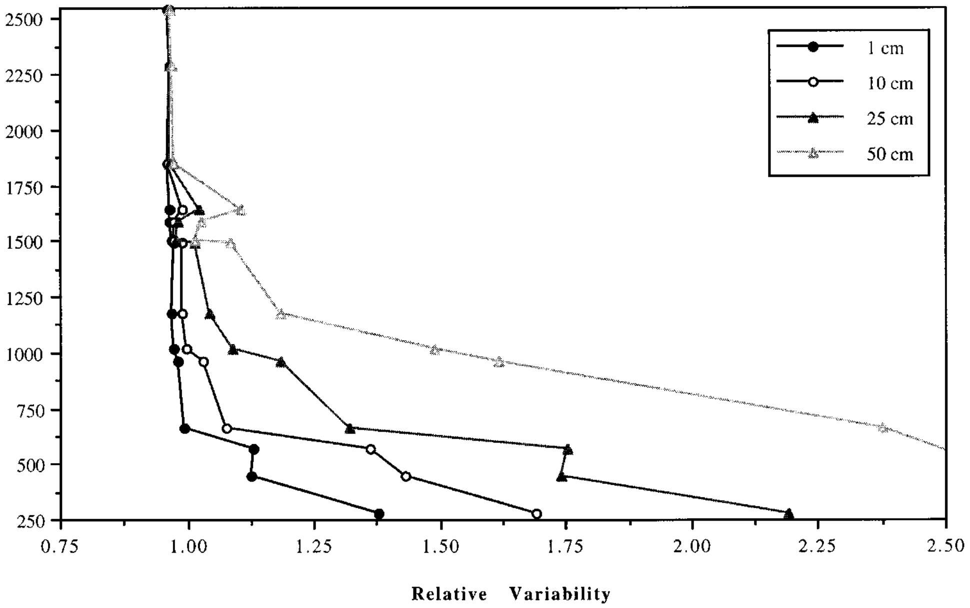

Figure 10. Relative variability of snow duration with height for snow-depth thresholds of 1, 10, 25, and 50 cm.

mean. While variances of snow duration are greater at higher elevations than at lower levels, so are the mean values; taking the ratio of the standard deviation to the mean removes the altitudinal dependency of the variance and mean, thereby highlighting the variability of this parameter in a normalized manner. This is illustrated in Figure 10, where the relative variability of snow duration for threshold levels ranging from 1–50 cm are given. The relative variability is high in all cases at low elevations, but becomes damped out with height. For the 1-cm threshold, the relative variability becomes small and quasi-independent of height between 750 and 1000 m, whereas for the 25-cm threshold, the damping occurs at and above 1500 m. For snow thresholds of 100 cm and more, the variability becomes independent of heights beyond 2000–2200 m. Figure 10 simply states that, in the sequence of cold and subsequently mild winters recorded over the last 15 years, altitudes above 800 m have been relatively insensitive to climatic fluctuations for a 1-cm snow threshold, as evidenced by their low variability above this height, whereas levels below 1800 m have been sensitive to changes in large-scale forcings for snow depths of 50 cm or more. Another means of formulating this conclusion is that, during mild winters, snow tends not to accumulate at low elevations, and only above 1500–2000 m is deeper snow likely to occur, whatever the temperature anomalies associated with a particular winter season.

These unusual winters have been used as a surrogate for snow conditions in the Alps in a warmer global atmosphere forced by enhanced greenhouse gas concentrations, as projected by the IPCC (1990, 1995). Studies by analogy can be of use in evaluating the response of a number of systems to changes in snow cover and duration in a warmer world. A review of potential impacts is given by Beniston (1994) and Beniston et al. (1996).

The 1980–1994 period has undergone a significant warming in the latter part of the period, with temperature anomalies ranging from 1–4 K according to geographical location and altitude (Beniston et al., 1994). Minimum temperatures have exhibited the largest temperature amplitudes (Beniston and Rebetez, 1995) and, as already mentioned, the magnitude of these anomalies increases with height. General circulation model (GCM) studies of climate change under enhanced greenhouse gas concentrations have shown that Europe may experience an average temperature rise of 2–4 K by the middle of the next century (Giorgi et al., 1990, 1992; Marinucci and Giorgi, 1992). High-resolution nested model simulations have shown that the Alps are expected to be highly sensitive to warming over Europe and may amplify the warming signal (Marinucci et al., 1995). Winter temperature differences relative to the present-day baseline may exceed 4 K in certain parts of the Alpine region (Beniston et al., 1995).

These GCM projections for temperature changes are close to the anomalies recorded in the second half of the 1980s, so that some conclusions may be drawn by analogy for future snow amount and duration in a warmer global climate. For example, Föhn (1991) has suggested that one potential effect of global warming in the Swiss Alps is likely to be a delay in the first snowfall and a reduction in the length of snow cover (which has been observed in the 1980s and 1990s); this would in turn increase early seasonal runoff, leading to drier soil and vegetation in summer, with a greater potential for forest fires in already sensitive areas. Analysis of satellite data from the 1980s and early 1990s has shown that lowlands around the Alps experience about 3–4 weeks less snow cover than earlier this century, and this tendency is likely to accelerate in a warmer climate (Baumgartner and Apfl, 1994). The impact of climate change on snow in the French Alps have been undertaken by Martin et al. (1994) and Martin (1995) with a physically-based snow model coupled to a meteorological analysis system. The two systems have been validated by comparing measured and simulated snow depth at 37 sites in the French Alps for the period 1981/1991. Sensitivity studies show that lower elevations (i.e., below 1500 m) are extremely sensitive to small changes in temperature, especially in the southern part of the French Alps. According to Martin (1995), variations of precipitation amount influences the maximum snow depth (or snow water equivalent), more than snow cover duration. Other studies reported for different mountain regions of the world support these conclusions (e.g., Hewitt, 1994; Kuhn, 1989).

It would be difficult to draw more far-reaching conclusions for climate impacts on the basis of the short series of anomalously warm winters experienced in the Alps; this is particularly the case for ecosystem responses to climate change which generally occur over longer time-scales. The run of mild winters in the Alps has, however, had a measurable effect on snowline altitude, snow amount and duration, which in turn has influenced flow regimes in a number of hydrological basins originating in the mountains. Perturbations to hydrological regimes in a changed climate will certainly be the norm in the next century (e.g., Bultot, 1992; Gleick, 1987; Krenke et al., 1991; Leavesly, 1994), because of the different timings of the beginning and end of the snow season, and the overall reduction in the duration of the mountain snow-pack. The sparsity of snow has also had significant economic impacts on mountain communities in the late 1980s and early 1990s, which are heavily dependent on winter sports for their income. The conclusion that snow amount and duration has been sensitive to changes in climate over the last 15 years at altitudes below 1500–2000 m is consistent with the rise in average snowline projected under a warmer global climate (IPCC, 1995); these conclusions could already help certain communities in preparing adaptation strategies for the future, for example through diversification of tourism activities rather than relying solely on the ski industry in Winter.

4. Conclusions

This paper has made a survey of snow statistics in the Swiss Alps over the last 50 years for a limited number of representative sites, with an additional focus on 12 climatological stations for the anomalously cold and warm 15-year period from 1980–1994.

The study has confirmed other findings that snow in the Alps is highly variable from year to year, but that there are some long-term cycles which appear to be governed by shifts in large-scale forcings. These are represented by the North Atlantic Oscillation index, whose influence extends to the Alps when the index is positive and high; the pressure signal from the NAO index is amplified in the Alpine region. Over the last 15 years, which saw a number of cold winters accompanied by significant amounts of snow, followed since the second half of the 1980s by some very mild winters with little snow, the dominant feature has been the variations of the regional-scale pressure field. The anomalously warm winters have resulted from the presence of very persistent high pressure episodes which have occured essentially during periods from late Fall to early Spring. The timing of the inception and subsequent persistence of high pressure episodes, and their frequency of occurence during a particular Winter will therefore determine the amount of snowfall and accumulation throughout the season. Persistent highs in late Fall and recurrence in Winter will lead to low accumulation in the crucial periods at the beginning of the season, and early melting because the snow-pack does not reach depths sufficient to ‘survive’ the first warm periods in early Spring. The study has shown that this is particularly true for low to medium elevation sites in the Alps; above the altitudinal range 1500–2000 m, the snowpack is much less sensitive to the shifts in large-scale forcings, because snow will likely accumulate at these altitudes whenever there is precipitation, and even anomalous temperatures induced by high-pressure subsidence are unlikely to be sufficient to initiate melting.

In the context of the issues related to climatic change forced by enhanced greenhouse-gas concentrations, the anomalously warm winters experienced in recent years can serve as a benchmark for the likely response of snow, and associated systems such as hydrology and glaciers, to a generally warmer world. The sensitivity of snow to large-scale forcings below about 2000 m is a clear indication that there will likely be less snow, and that the snow season will be shorter. This is in line with a number of other studies carried out by different groups and summarized by the IPCC Second Assessment Report on the impacts of climate change (IPCC, 1995); however, the present study has provided more than speculative evidence about which levels will be most vulnerable to climate change. The conclusions presented here can provide guidance to future environmental and economic planning in the Alps, particularly for activities related to Winter tourism.

References

Abegg, B. and Froesch, R.: 1994, ‘Climate Change and Winter Tourism: Impact on Transport Companies in the Swiss Canton of Graubünden’, in Beniston, M. (ed.), *Mountain Environments in Changing Climates*, Routledge Publishing Company, London and New York, pp. 328–340.

Barry, R. G.: 1992c, ‘Mountain Climatology and Past and Potential Future Climatic Changes in Mountain Regions: A Review’, *Mountain Research and Development* **12**, 71–86.

Baumgartner, M. F. and Apfl, G.: 1994, ‘Monitoring Snow Cover Variations in the Alps Using the Alpine Snow Cover Analysis System (ASCAS)’, in Beniston, M. (ed.), *Mountain Environments in Changing Climates*, Routledge Publishing Company, London and New York, pp. 108–120.

Beniston, M. (ed.): 1994, *Mountain Environments in Changing Climates*, Routledge Publishing Co., London and New York, p. 492.

Beniston, M., Rebetez, M., Giorgi, F., and Marinucci, M. R.: 1994, ‘An Analysis of Regional Climate Change in Switzerland’, *Theor. and Appl. Clim.* **49**, 135–159.

Beniston, M., Rebetez, M.: 1995, ‘Regional Behavior of Minimum Temperatures in Switzerland for the Period 1979–1993’, *Theor. and Appl. Clim.* **53**, 231–243.

Beniston, M., Fox, D. G., Adhikary, S., Andressen, R., Guisan, A., Holten, J., Innes, J., Maitima, J., Price, M., and Tessier, L.: 1996, ‘The Impacts of Climate Change on Mountain Regions’, *Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, Chapter 5, Cambridge University Press, pp. 190–213.

Bradley, R. S. and Jones, P. D.: 1992, *Climate Since AD 1500*, Routledge Publishing Company, London and New York, p. 692.

Bultot, F.: 1992, ‘Repercussions of a CO_2 Doubling on the Water Balance – a Case Study in Switzerland’, *J. Hydrol.* **137**, 199–208.

Fitzharris, B. B.: 1989, ‘Impact of Climate Change on the Terrestrial Cryosphere in New Zealand’, *Summary paper*, Department of Geography, University of Otago, New Zealand.

Föhn, P.: 1991, ‘Les hivers de demain seront- ils blancs comme neige ou vert comme les prés?’, WSL/FNP (éd.), *Argument de la Recherche* **3**, 3–12.

Giorgi, F.: 1990, ‘On the Simulation of Regional Climate Using a Limited Area Model Nested in a General Circulation Model’, *J. Clim.* **3**, 941–963.

Giorgi, F., Marinucci, M. R., and Visconti, G.: 1992, ‘A $2 \times CO_2$ Climate Change Scenario over Europe Generated Using a Limited Area Model Nested in a General Circulation Model. II: Climate Change’, *J. Geophys. Res.* **97**, 10,011–10,028.

Gleick, P. H.: 1987, ‘Regional Hydrologic Consequences of Increases in Atmospheric CO_2 and Other Trace Gases’, *Clim. Change* **10**, 137–161.

Hewitt, M.: 1994, ‘Modeled Changes in Snow Cover in the Australian Alps under Enhanced Greenhouse Gas Concentrations’, *Proc. International Symposium on Snow and Climate*, Geneva, September 22–23, 1994.

Hurrell, J.: 1995, ‘Decadal Trends in the North Atlantic Oscillation Regional Temperatures and Precipitation’, *Science* **269**, 676–679.

IPCC: 1990, Houghton, J. T., Jenkins, G. J., and Ephraums, J. J. (eds.), *Intergovernmental Panel on Climate Change, Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, p. 365.

IPCC: 1996, *Intergovernmental Panel on Climate Change, Climate Change, The IPCC Second Assessment Report*, Working Groups I, II and III, Cambridge University Press, in press.

Kuhn, M.: 1989, ‘The Effects of Long-Term Warming on Alpine Snow and Ice’, in Rupke, J. and Boer, M. M. (eds.), *Landscape Ecological Impact of Climate Change on Alpine Regions*, Lunteren, The Netherlands.

Kushnir, Y.: 1994, ‘Interdecadal Variation in North Atlantic Sea Surface Temperature and Associated Atmospheric Conditions’, *J. Clim* **7**, 141–157.

Marinucci, M. R. and Giorgi, F.: 1992, ‘A $2 \times CO_2$ Climate Change Scenario over Europe Generated Using a Limited Area Model Nested in a General Circulation Model. I: Present Day Simulation’, *J. Geophys. Res.* **97**, 9,989–10,009.

Marinucci, M. R., Giorgi, F., Beniston, M., Wild, M., Tschuck, P., and Bernasconi, A.: 1995, ‘High Resolution Simulations of January and July Climate over the Western Alpine Region with a Nested Regional Modeling System’, *Theor. and Appl. Clim.* **51**, 119–138.

Martin, E.: 1995: ‘Modélisation de la climatologie nivale des Alpes françaises’, *PhD Dissertation*, Université Paul Sabatier, Toulouse, France, p. 232.

Martin, E., Brun, E., and Durand, Y.: 1994, ‘Sensitivity of the French Alps Snow Cover to the Variation of Climatic Variables’, *Annales Geophysicae* (in press).

Moses, T., Kiladis, G. N., Diaz, H. F., and Barry, R. G.: 1987, ‘Characteristics and Frequency Reversals in Mean Sea-Level Pressure in the North Atlantic Sector and their Relationships to Long-Term Temperature Trends’, *J. Climatol.* **7**, 13–30.

Price, M. F.: 1994, ‘Should Mountain Communities Be Concerned about Climate Change?’, in Beniston, M. (ed.), *Mountain Environments in Changing Climates*, Routledge Publishing Company, London and New York, pp. 431–451.

Rebetez, M.: 1996, ‘Public Expectation as an Element of Human Perception of Climate Change’, *Clim. Change* (in press).

Slatyer, R. O., Cochrane, P. M., and Galloway, R. W.: 1984, ‘Duration and Extent of Snow Cover in the Snowy Mountains and a Comparison with Switzerland’, *Search* **15**, 327–331.

Wanner, H.: 1994, ‘The Atlantic-European Circulation Pattern and Its Relevance for Climate Change in the Alps’, *Report 1/94 to the Swiss National Science Foundation*, 15 pp.

Witmer, U., Filliger, P., Kunz, S., and Kung, P.: 1986, *Erfassung, Bearbeitung und Kartiering von Schneedaten in der Schweiz, Geographica Bernensia G25*, University of Bern, Switzerland, 215 pp.

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