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Regional Behavior of Minimum Temperatures in Switzerland for the Period 1979–1993

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With 12 Figures

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Summary

A series of anomalously cold and warm winters which occurred in Switzerland during the 15-year period from 1979 to 1993 has been analyzed in detail in terms of temperature minima. The warm winters between 1988–1992 were particularly marked in the Alps, where lack of snow had severe consequences for the tourist-based economies of mountain communities. The investigations presented here focus primarily on minimum temperature records for up to 88 climatological observing sites distributed over Switzerland.

Analyses of the departures of temperature minima from the 15-year means in warm and cold winters has shown that there is a very significant altitudinal dependency of the anomalies except at low elevations which are subject to fog or stratus conditions; the stratus tends to decouple the underlying stations from processes occurring at higher altitudes. It is also shown that there is a switch in the gradient of the temperature anomaly with height from cold to warm winters. For warm winters, the higher the elevation, the stronger the positive anomaly; the reverse is true for cold winters. The statistics for the 88 observational stations provide a measure of the damping of the climate signal as an inverse function of height. The altitudinal dependency of temperature departures from the mean are the most important feature, followed by latitudinal effects (north and south of the Alps); continentality is not seen to be a major factor in determining the geographical distribution of temperature anomalies at this scale.

The present investigation also emphasizes the fact that high elevation records can more readily identify significant interannual climatic fluctuations than at lower-elevation sites. This is also likely to be the case for longer-term climate change, where possibe greenhouse-gas warming would presumably be detected with more clarity at higher elevations. This type of study can help orientate future high-resolution climate model studies of climate change and in particular the assessment of model capability in reproducing a range of possible temperature anomalies and their altitudinal dependency.

1. Introduction

In a recent paper (Beniston et al., 1994: hereafter BRGM after the initials of the four co-authors), it was shown that climate change in this century in Switzerland has been dominated in the latter part of the climatological record by anomalously high pressure anomalies, particularly in the winter. As mentioned in BRGM, over 25% of the persistent high pressure episodes this century exceeding the 965 hPa threshold at Zürich (approximately equivalent to a sea-level reduced pressure of 1030 hPa) have occurred in the 1980s. These persistent periods of elevated pressure over the Alpine region in the second half of the 1980s and early 1990s were accompanied by anomalously high temperatures, particularly for the minima, and significant reductions in precipitation. At elevations below 1,500 m above sea level (ASL), snow depth and duration were among the lowest recorded this century for several years in a row, causing much economic adversity for economic sectors dependent on winter snowfall (see for example Abegg et al., 1994). This led to media and public speculation that the series of anomalous winters may have been the first tangible sign of the impacts of global warming. BRGM showed that the pressure anomalies were strongly linked to synoptic scale forcings defined by the North Atlantic Oscillation Index, which is a measure of the strength of the westerly flow across the North Atlantic and is controlled essentially by sea-surface temperatures. As a follow-up to the detailed analysis described in BRGM, this investigation reports on the climatological anomalies observed in the Swiss Alps for the 15-year period from 1979–1993. This period has been chosen because it exhibits two very distinct series of cold and warm winters, which may be illustrative of a shift in climate patterns during the 15-year sampling period.

The focus in this paper will be on the minimum temperature record, because it was shown in BRGM that the minimum temperature trends for Switzerland are far more significant than the corresponding trends for the maxima. This is a conclusion which has been reported by a number of investigators, such as Balling (1992) and Karl et al. (1993). In the latter publication, the authors stress the fact that, over a significant part of the continental land masses in both hemispheres, minimum temperatures have risen over the last 40 years at a rate three times faster than the maxima. The figures cited are 0.84 and 0.28 K for the period from 1951–1990, respectively. Because of the asymmetry between the relative trends of the maxima and minima, it is hypothesized here that minimum temperature trends may provide clearer evidence for an early detection of anthropogenically-induced climate change than the maximum temperature trends. However, the analysis of mimimum temperature records for climate change studies is not trivial, particularly in complex mountain regions such as the Alps, as there are a number of factors (cold air pools, stratiform clouds and fog, valley breezes, etc.) which tend to contaminate the observations and thereby obscure any climate signals of global origin. This paper will therefore attempt to disentangle some of these complicating factors in such a manner that significant shifts in climate may be more readily identified.

Barry (1992) has stated that in addition to global- or regional-scale forcings, climate in mountainous regions is controlled by four principal factors, namely altitude, latitude, continentality, and topography. The geographical characteristics of minimum temperatures will be illustrated in terms of Barry's criteria, namely location (latitude, continentality) and site (altitude, topography), based on data from a set of 88 Swiss climatological stations. An overview will be given of the trends which have been observed during the 15-year sampling period, and then an analysis will be made of the regional characteristics of both the "warm" and "cold" anomalies of this period.

One of the motivations behind such a study, in addition to investigating some of the fundamental processes involved, is to link observational data to climate model data. High-resolution climate model experiments conducted over the Alpine area (Beniston et al., 1993; Marinucci et al., 1995) have shown that there exist significant discrepancies between model results for current climate and climatological observations in the Alps and surrounding lowlands. If we are to have greater confidence in model projections for enhanced greenhouse gas scenarios in a complex region such as the Alps, regional climate models should be in a position to simulate not only the means of climate variables in a particular region, but also the variability around those means. This variability can be altitudinally-dependant, as will be shown in this paper, and it is essential for models to reproduce this dependency if their results are to be meaningful. The altitudinal gradients of not only the means but also the anomalies have a number of consequences for the response of different environmental systems in the mountains, particularly snow, ice, and hydrology, but also vegetation and forests (Beniston, 1994). Any studies of the possible impacts of climate change on these systems requires climatological data from high-resolution models which are capable of reproducing these features in complex terrain.

2. Climatological Stations and Distribution

Up to 88 climatological stations in Switzerland have been used in this analysis. Their distribution is illustrated in Fig. 1, which depicts the four principal climatological zones defined by Baeriswyl and Rebetez (1995):

- The Jura Mountains: this mountain range runs along the Western boundary of Switzerland. It consists of a karstic-type landscape with a series of parallel ridges separated by wide, flat valleys.

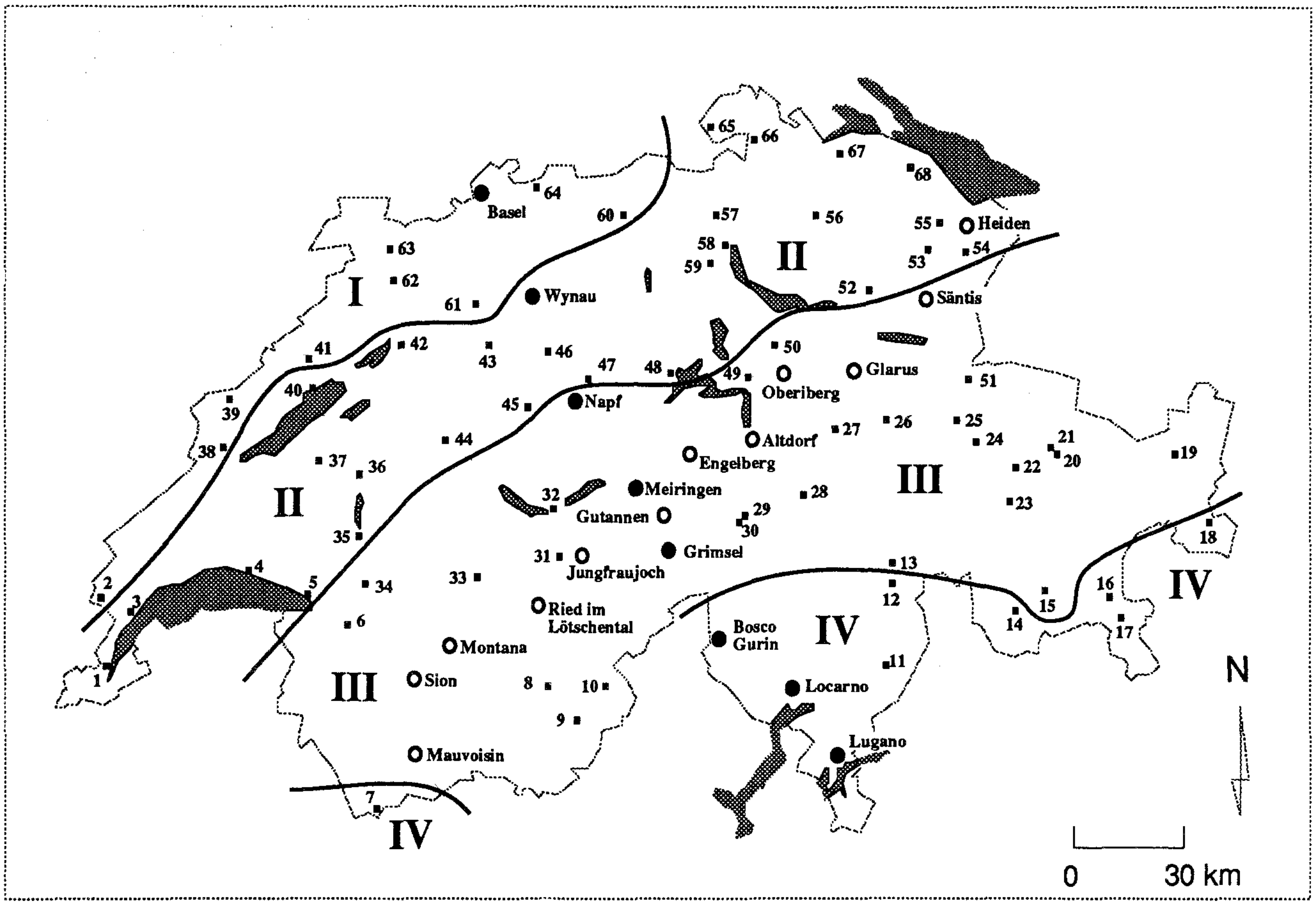

Fig. 1. Map of Switzerland, illustrating the 88 climatological stations used in this study and the four principal climatological regions of the country. The stations are listed in Table 1 in the text. Closed circles represent the "N-S transect" stations discussed in the text, and the open circles the "E-W transect" stations

The average elevation is in the vicinity of 1,000 m, with crests often exceeding 1,500 m;

- The Swiss Plateau: the Plateau lies between the Jura and the Alps, and is oriented SW–NE from the Lake of Geneva region to the Lake of Constance. The elevation range is between 400 and 800 m; the topography is rarely flat and consists of rolling hills and valley systems;
- The Alps: these mountains cover over 60% of the surface area of Switzerland and consist of several ranges, the principal ones being the Valais or Pennine Alps, the Bernese Oberland, the Central Alps, and the Grisons. Altitudinal differences are extreme, with many mountain summits exceeding 4,000 m;
- The Southern Alps: this region encompasses not only the southern part of Switzerland (Tessin and the Italian-speaking valleys of the Grisons) but also a number of mountain passes located on the divide between the Mediterranean basin and the northern Alps, such as the Grand Saint Bernard or the Bernina, whose climatological characteristics are more commonly associated with those of the Southern Alps.

While a more detailed partitioning of climatological regions is possible, the minimum four regions used here have been deemed sufficient for the purposes of this investigation. Table 1 provides an overview of the station elevations for the four climatological regions just described. The data have been compiled on the basis of the Swiss Climatological Data Base, a computerized data set managed by the Swiss Meteorological Institute (Bantle, 1984).

The Jura stations comprise 10 data points, the Plateau 29, the Alps 39, and the Southern

Table 1. *List of Climatological Stations and Altitudes.* Numbers refer to the locations of these stations on the map in Fig. 1; NS refers to stations on the North-South transect, identified by station name and closed circles in Fig. 1; EW refers to the East-West transect, identified by station name and open circles in Fig. 1

Jura		Plateau		Alps		Southern Alps	
Station	Alt	Station	Alt	Station	Alt	Station	Alt
Balmberg (61)	1075	Altstätten SG (54)	474	Abelboden (33)	1355	Bosco Gurin (NS)	1505
Basel (NS)	317	Bern-Liebefeld (44)	570	Altdorf (EW)	451	Gd St Bernard (7)	2479
Chaumont (41)	1141	Biel (42)	434	Alvaneu (23)	1175	Grono (11)	357
Delémont (63)	416	Broc (35)	680	Andermatt (30)	1442	Löbbia (14)	1420
La Brévine (39)	1042	Changins (3)	435	Arosa (22)	1847	Locarno (NS)	379
Dôle (2)	1672	Ebnat Kappel (52)	629	Bad Ragaz (51)	496	Lugano (NS)	276
La Fretaz (38)	1202	Fribourg (36)	634	Château d'Oex (34)	980	Bernina (16)	2256
Les Rangiers (62)	856	Genève (1)	430	Chur (24)	586	Poschiavo (17)	1078
Rheinfelden (64)	271	Güttingen (68)	438	Davos (20)	1590	S Maria/M (28)	1390
Unterbözberg (60)	514	Haidenhaus (67)	694	Disentis (28)	1180	S. Bernardino (12)	1628
		Hallau (65)	450	Einsiedeln (50)	910		
		Heiden (EW)	811	Elm (26)	962		
		Huttwil (46)	639	Engelberg (EW)	1018		
		Langnau (45)	695	Glarus (EW)	470		
		Luzern (48)	456	Grächen (8)	1617		
		Menzberg (47)	1035	Grimsel (NS)	1950		
		Montreux (5)	408	Gütsch (29)	2288		
		Neuchâtel (40)	487	Guttannen (EW)	1055		
		Oeschberg (43)	482	Hinterrhein (13)	1619		
		Payerne (37)	491	Interlaken (32)	574		
		Pully (4)	461	Jungfraujoch (EW)	3572		
		Schaffhausen (66)	457	Mauvoisin (EW)	1841		
		St. Gallen (55)	664	Meiringen (NS)	832		
		Stein AR (53)	786	Montana (EW)	1495		
		Tänikon (56)	536	Mürren (31)	1639		
		Uetliberg (59)	810	Napf (NS)	1408		
		Wynau (NS)	422	Oberiberg (EW)	1090		
		Zürich Airport (57)	431	Ried/Lötsch. (EW)	1480		
		Zürich SMA (58)	569	Saas Almagell (9)	1680		
				Säntis (EW)	2500		
				Schwyz (49)	448		
				Scuol (19)	1295		
				Sepey (6)	1267		
				Sils Maria (15)	1802		
				Simplon Dorf (10)	1495		
				Sion Airport (EW)	483		
				Tierfehd (27)	810		
				Vättis (25)	948		
				Weissfluhoch (21)	2540		

Alps an additional 10 points. For these 88 stations, uninterrupted climatological data exist for at least the 15-year sampling period, allowing exhaustive statistical analyses to be made on unique spatial and temporal scales.

3. Data Analysis for the Period 1979–1993

3.1 *Temporal Distribution of Temperature*

Departures from the 15-year climatological mean period 1979–1993 have been computed on a seasonal basis for the same four stations analyzed in

BRGM, namely Davos, Lugano, Säntis, and Zürich. Figure 2 illustrates the anomalies of minimum temperatures; in all figures, three-month averages for the four seasons are represented by the abbreviations DJF (December, January and February), MAM (March, April and May), JJA (June, July and August), and SON (September, October and November).

The minimum temperatures exhibit in general an abrupt increase in the winter and spring anomalies for the years between 1988 and 1990, then again in 1992 and 1993 at the high elevation sites, whereas prior to 1988, anomalies were, in broad terms, lower than average if one excludes the particularly warm summer of 1983. Zürich exhibits also a very warm summer period in 1991 which is not reflected quite as much at the other locations. The minimum temperature anomalies are seen to be particularly strong for the winter period (DJF), followed by the spring (MAM). Temperature anomalies exceed 2 °C at low elevation sites and 4 °C at higher elevations. This is consistent with other analyses of climate data in Switzerland which have pointed to the fact that temperature variance generally increases with altitude (Rebetez, 1994).

The strong departures from the 15-year 1979–1993 mean period in three successive years at the end of the 1980s and again in the early 1990s is indicative of a significant shift in climate over this period; these are linked to changes in the westerly flow entering Western Europe. The positive anomalies correspond to periods of persistent high pressure over the Alpine region, related to surface pressure fields over the western Mediterranean and the Iberian Peninsula which were systematically higher than their climatological averages during these months. The persistence of high-pressure over the Alps and the associated subsidence fields resulted in large temperature departures from the mean period with severe consequences for winter snow and hydrology. These were shown in BRGM to be closely linked to the North Atlantic Oscillation Index (NAO), i.e., the pressure difference between the Azores and Iceland which provides a measure of the strength of flow over the Atlantic. The pressure statistics emphasized the appearance of a new and anomalous behavior in the 1980s, where pressure reached annual average values far higher than at other times this century; winter (DJF) pressure anomalies are particularly high in the 1980s and are well correlated with the NAO Index at this time. This points to shifts in North Atlantic westerly flow fields to more northerly latitudes as being the principal mechanism influencing the Alpine region over the sampling period.

A careful analysis of the data shows that the individual months which exhibit the strongest departures from the mean are the January minima; this is also the month which generally experiences the lowest annual temperatures in Switzerland. Figure 3 shows the evolution of January minimum temperatures for each year of the sampling period at the four stations. It is seen that a significant shift occurs from 1987 onwards, with a remarkable increase of winter temperatures until 1990, after which time they remain at an anomously high level; it would appear that the system has not recovered from whatever climate mechanisms triggered the warming trend in the latter part of the 1980s. A similar analysis of July trends (not illustrated here) indicates that apart from a very warm summer in 1983, no major anomalies in the rest of the period are apparent; in fact, the maxima begin to decrease from 1991 to 1993. In terms of the annual mean temperatures which were discussed in BRGM, it is clear that the strong positive temperature anomalies of the winter period are generating the bias in the annual record and are the principal contributor to overall warming in the 1980s.

It is apparent from this discussion and Figs. 2 and 3 that there is an altitudinal dependency of warming with altitude, i.e., the higher the elevation, the greater the positive winter minimum temperature anomaly. This is indicative of one or several large-scale forcing mechanisms which become more perceptible in the observations the higher the elevation; at high altitudes, stations are closer to the free atmosphere and are less likely to be contaminated by local site features, particularly in stable winter situations. Because it is difficult to support this hypothesis on the basis of only four sets of observations, it will now be investigated on the basis of the 88 observational stations, representative of the four broad Swiss climatological zones.

3.2 Spatial Distribution of Temperature Anomalies

Based on Figs. 2 and 3, the January minimum temperature series can be broadly separated into two five-year periods, one with "cool anomalies" from 1983–1987, and one with "warm anomalies"

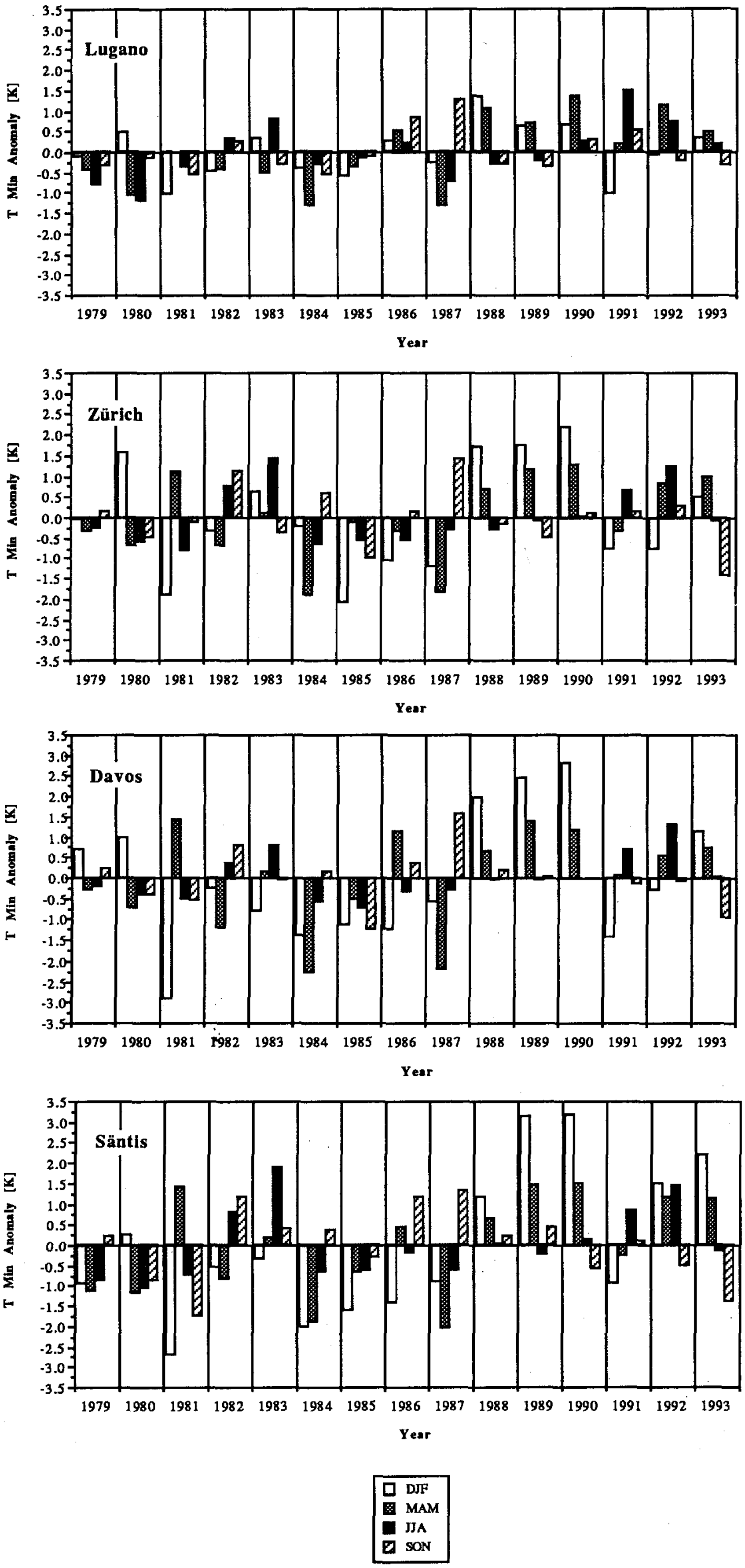

Fig. 2. Seasonal departures of minimum temperatures from the 15-year mean period 1979–1993 for Lugano, Zürich, Davos, and Säntis

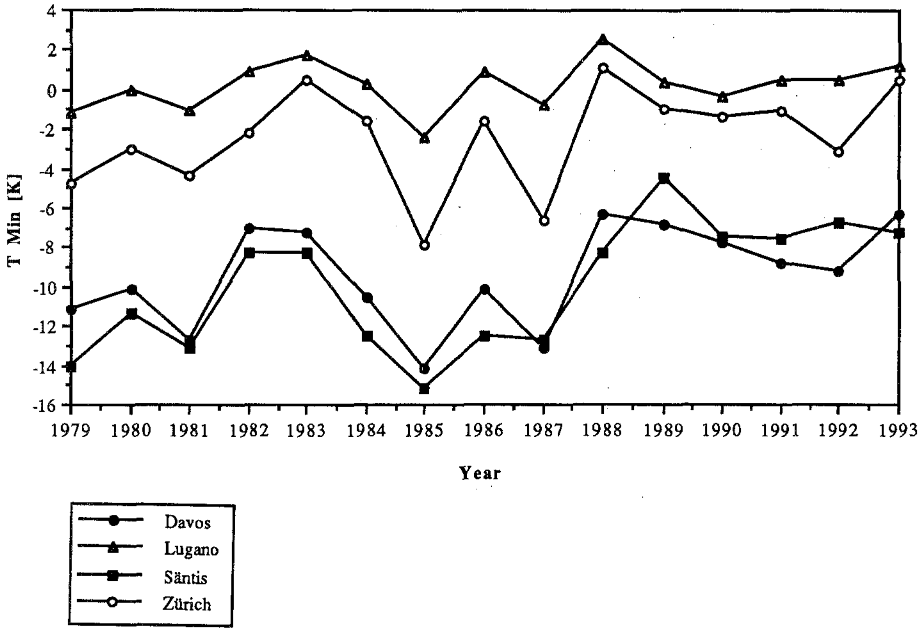

Fig. 3. Average January minimum temperature trends during the period 1979–1993 for Lugano, Zürich, Davos, and Säntis

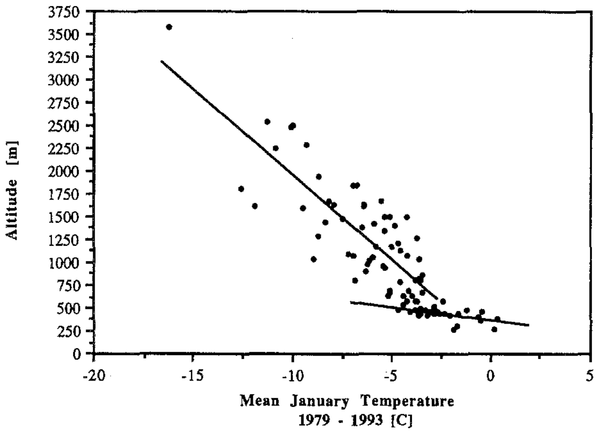

Fig. 4. Altitudinal distribution of mean minimum temperatures at the 88 climatological stations, based on the 15-year averages of the period 1979–1993

from 1988–1992. Figure 4 illustrates the distribution of the mean 15-year average January temperatures with height; at low elevations, the average lapse rates are very high, close to 5 K/100 m. The range of temperatures reflects different geographical conditions: some stations are located south of the Alps, such as Lugano, where milder temperatures can be expected, while others are located in the cold air pool which frequently forms over the Swiss Plateau in winter, accompanied by fog or stratus clouds. At higher elevations, the average lapse rate becomes steeper and attains a characteristic value of about 0.5 K/100 m; the spread of data around this mean vertical temperature gradient is mainly indicative of specific site conditions, which determine long-term means; some stations may be located on north or south-facing slopes, on mountain summits, or at the bottom of valleys where temperature inversions may often occur.

Figure 5 illustrates the altitudinal distribution of minimum temperature anomalies for the "warm anomalous" period, with individual symbols representing stations in each of the four climatological zones; Fig. 5a shows the distribution for the entire set of stations, and Fig. 5b for the Alpine stations alone. The correlation coefficients between temperature anomalies and altitude for the entire data set and for the four climatological regions are given in Table 2.

Figure 5 confirms that the anomalous behavior of the minima is altitudinally-dependent, i.e., the higher the elevation, the greater the positive anomaly. The scatter around the trend line is related to local site characteristics. For example, the Jura station of La Brévine (cf. Fig. 5a) is located at the bottom of a closed valley where strong temperature inversions frequently occur in winter; cold air pools tend to persist over long periods and only disappear if a significant external perturbation occurs. The persistent cold air pools in winter explains the strong departure from the other stations; La Brévine holds the cold record for Switzerland, with temperatures slightly below −40 °C recorded in 1985 and 1987.

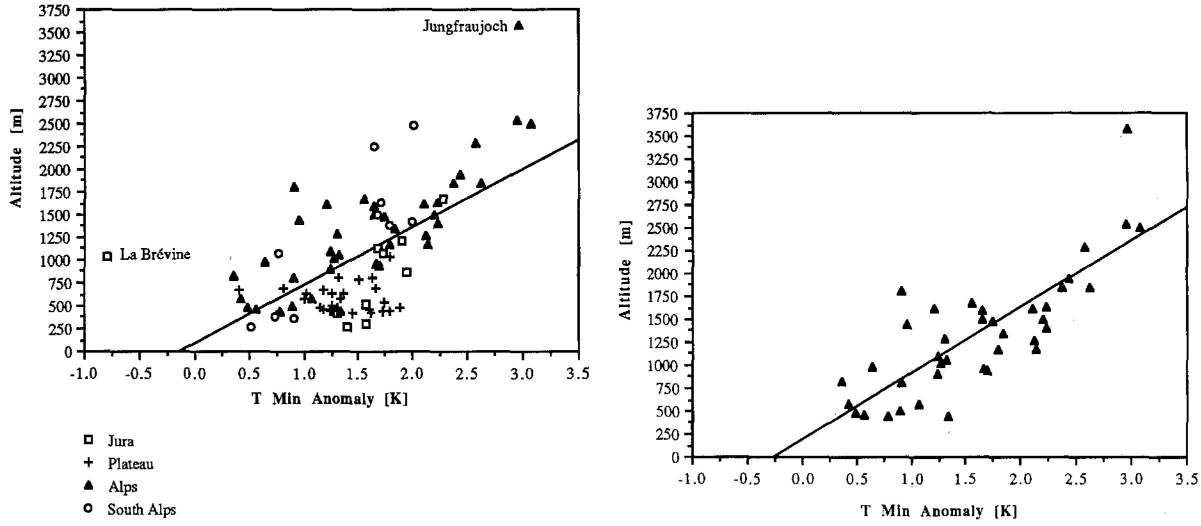

Fig. 5. a) Height-temperature anomaly relationship for the "warm" Januaries of the 5-year period from 1988–1992 at all 88 climatological stations. b) As 5a, except for the 39 stations in the Alpine climatological region

Table 2. *Correlation Coefficient for Relationship Between Minimum Temperature Anomalies and Altitude for the Average 1988–1993 Januaries.* T-test of R at the 99% significance level is provided; in brackets, limit of t-distribution above which R is significant

Data Set	R	t-test (99% level)
All Stations	0.63	7.52 (2.44)
Jura (without La Brévine)	0.88	4.90 (3.50)
Plateau	0.05	0.26 (2.77)
Alps	0.80	8.11 (2.71)
Southern Alps	0.84	4.38 (3.36)

Many of the locations to the left of the linear regression line in both Fig. 5a and 5b are stations which are located in valleys subject to strong and persistent temperature inversions; those to the right, which exhibit warmer anomalies than those predicted by the regression are located in regions more commonly exposed to wintertime stratus, which traps outgoing infrared radiation at night and maintains nocturnal temperatures warmer than they would be in the absence of the cloud cover; some locations in this section of the diagram are also subject to occasional warming föhn effects. The Plateau station data lie almost all to the right of the regression line; the Plateau and some of the side valleys feeding into it are most subject to persistent stratus cover, which tends to have an average thickness of 200–500 m and an upper limit of between 800–1400 m. The stations lying beneath the stratus layer are essentially decoupled from processes occurring at higher elevations, as exemplified by the significant change in mean temperature lapse rates illustrated in Fig. 4.

Figure 6 shows the average monthly sunshine duration, expressed as a percentage of maximum

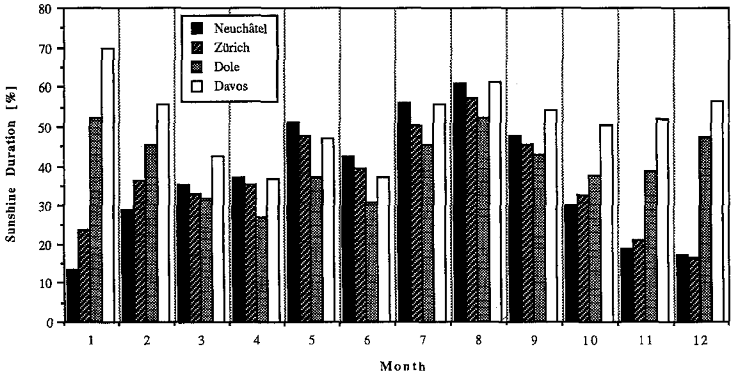

Fig. 6. Potential sunshine duration statistics at two low-level sites (Neuchâtel and Zürich, Swiss Plateau) and two high elevation sites (La Dôle, Jura, and Davos, Alps) as a measure of the persistence of fog and stratus conditions over the Swiss Plateau in winter

possible duration as a function of site and time of year, for the 1988–1992 period. It is seen that particularly from November to February, sunshine duration was particularly low in both Neuchâtel and Zürich (less than 20% in January) for the 5-year period, and relatively high in both the Jura station of La Dôle and the Alpine station of Davos (70% of maximum possible sunshine). The very low values over the Swiss Plateau are symptomatic of the presence of persistent stratus; the cloud cover in such situations is generally more dense during the nocturnal hour than during the day, so that for the winter period, the use of sunshine duration as a measure of persistance of fog or stratus beyond just the daylight hours is justified. Conversely in the mountains and in the absence of cloud-bearing synoptic perturbations, clear skies during the day will invariably be followed by clear skies at night.

The representativity of the Jungfraujoch station (indicated in Fig. 5), far removed from the predictor line, is open to question; the observation station is located on the northern side of the Sphinx Observatory, itself situated on a pass subject to a bimodal flow distribution, i.e., either northerly or southerly flow. It is suspected that the lack of sufficient exposure of the instruments to many of the characteristic flow régimes is responsible for the bias in the height/temperature anomaly relationship.

Table 3. *As Table 2, Except for January 1989*

Data Set	R	Significance (99%)
All Stations	0.74	10.20 (2.44)
Jura (without La Brévine)	0.95	48.05 (3.50)
Plateau	0.00	0.00 (2.77)
Alps	0.83	9.05 (2.71)
Southern Alps	0.89	5.52 (3.36)

When analyzing a single January, namely the highly anomalous winter of 1989, the relationship between temperature anomaly and altitude is even more remarkable, as illustrated in Fig. 7. Correlation coefficients are provided in Table 3.

The relationship between minimum temperature anomalies for this period and the altitude of the station is remarkable, even when taking into account the bias generated by the Plateau stations under the influence of the persistent winter stratus cover. This seems to be the only local site condition of importance in this study.

A similar analysis can be made of the "anomalously cold" period from 1983–1987; the results for minimum temperature anomaly vs height are illustrated in Fig. 8; the corresponding correlation analysis table is given in Table 4.

The figure shows that during cold winters, the anomalies are reversed with respect to warm winters, i.e., the higher the elevation, the more negative the anomaly. It is also noteworthy that the distribution of data around the regression line is also completely reversed with respect to Fig. 5; stations which were warmer than expected from

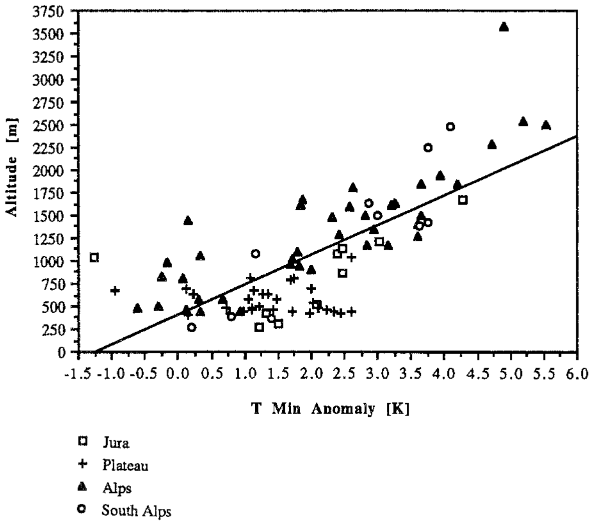

Fig. 7. Height-temperature anomaly relationship for the very warm January of 1989 for all 88 climatological stations

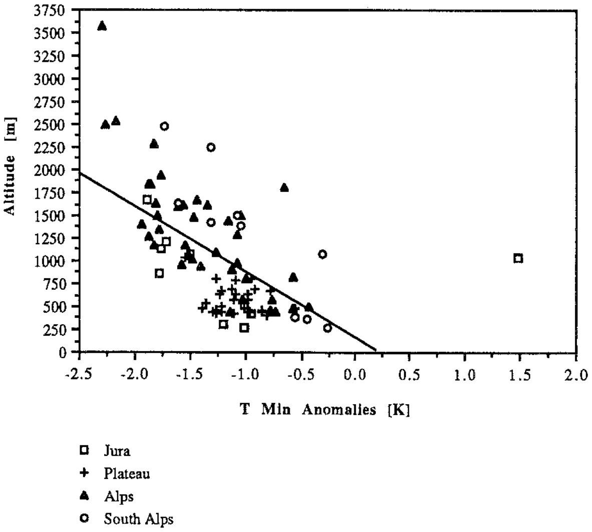

Fig. 8. Height-temperature anomaly relationship for the "cold" Januaries of the 5-year period from 1983–1987

Table 4. *As Table 2, Except for 1983–1987 Januaries*

Data Set	R	Significance (99%)
All Stations	−0.57	6.43 (2.44)
Jura (without La Brévine)	−0.89	5.16 (3.50)
Plateau	−0.22	1.17 (2.77)
Alps	−0.75	6.90 (2.71)
Southern Alps	−0.87	4.99 (3.36)

the predictor line are, during cold winters, colder than expected from the predictor. This is mainly due to the fact that even if the winters are characterized by stratus cover, they are also accompanied by very cold low-level temperatures and often snow on the ground which influences the net radiation balance and contributes to low nocturnal temperatures. Similar conclusions can be reached when interpreting data for individual "cold" Januaries during the period, such as the very cold winter of 1987 (not shown). Relationships between anomalies and height are statistically more significant for individual Januaries than for their average 1983–1987 values, a conclusion already reached when examining the warm anomalies (cf. Tables 2 and 3). The mechanism that distinguishes between anomalous warm and cold winters is sketched in Fig. 9.

This leads to the conclusion that the lower atmosphere tends towards lower stability during warm winters and higher stability during colder winters; the lower the elevation, the more the anomaly becomes damped out by surface, topographic and local climatic effects, as one would expect. The density of the Swiss climatological network allows this damping to be quantified, i.e., the trend line provides an attenuation gradient of the large-scale signal. It is also remarkable that the warm winter anomalies are characterized by a switch in the sign of this gradient, from negative to positive. Indeed, analyses of the mean January anomaly gradients over the 15-year period show these to be largely negative on average, thus indicating that the warm winters of the second half of the 1980s and the beginning of the 1990s are very much out of the ordinary. While it has been speculated that high elevations may indeed be more sensitive to climatic fluctuations than lower sites where climate variables become contaminated by local features, this study allows a quantitative evaluation of the relationship between a large-scale signal and the location at which it is measured.

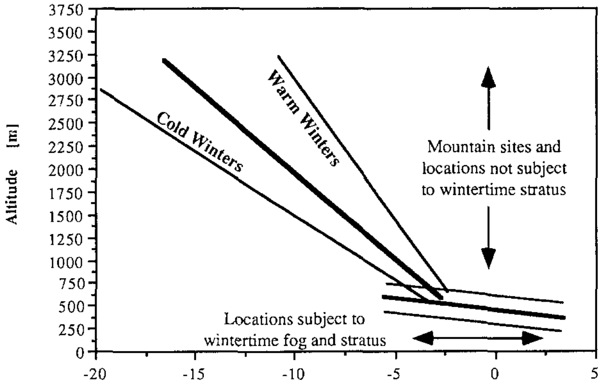

Fig. 9. Schematic diagram to illustrate the switch of temperature anomalies about the mean between warm and cold winters. The bold line represents the mean 15-year minimum temperature lapse rate for the 1979–1993 sampling period

3.3 *Influence of Latitude and Continentality on Temperature Anomalies*

In order to investigate whether the influence of latitude (north or south of the Alps) or longitude/continentality may also influence the nature of temperature anomalies, the "transect stations" illustrated in Fig. 1 will be used; these comprise 8 stations running NW–SE from Basel to Lugano, and 12 stations distributed SW-NE from Mauvoisin (Valais Alps) to Heiden (close to the Rhine River and Liechtenstein). The N-S line cuts across all four climatological regions, whereas the E-W section is confined to the Alpine zone.

Figures 10 and 11 provide an overview of average 1988–1992 January anomalies along the N-S and E-W transect, respectively. The altitudinal dependency of the anomaly is clearly visible in both figures, and it is apparent that there are also regional differences. These can be quantified to some extent by plotting the ratio of anomaly to height against N-S or E-W distance, as shown in Fig. 12. If the anomalies were everywhere perfectly correlated to altitude, then the resulting line linking this anomaly/height ratio and distance would be horizontal. The deviations from the ideally horizontal line are due primarily to site influences, as at Basel and Wynau for the N-S transect, related to the presence of stratus at this

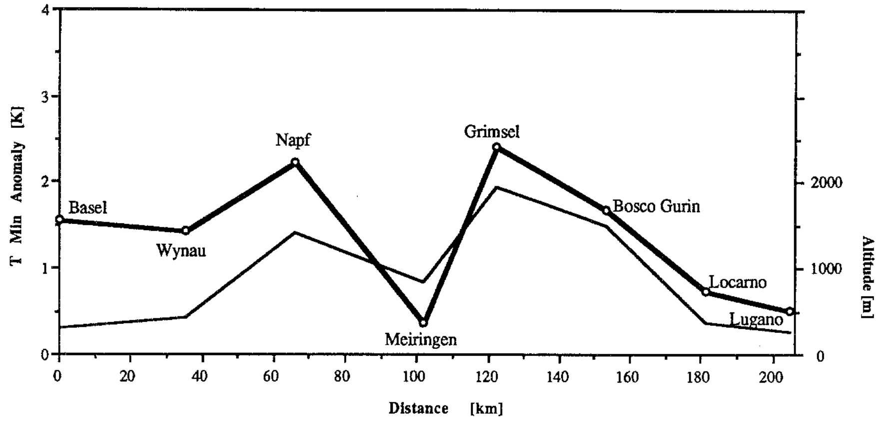

Fig. 10. Distribution of minimum temperature anomalies for the "warm" winters of 1988–1992 along the N-S transect illustrated in Fig. 1. The altitudinal profile (thin line) is also shown to provide an illustration of the height-anomaly relationship

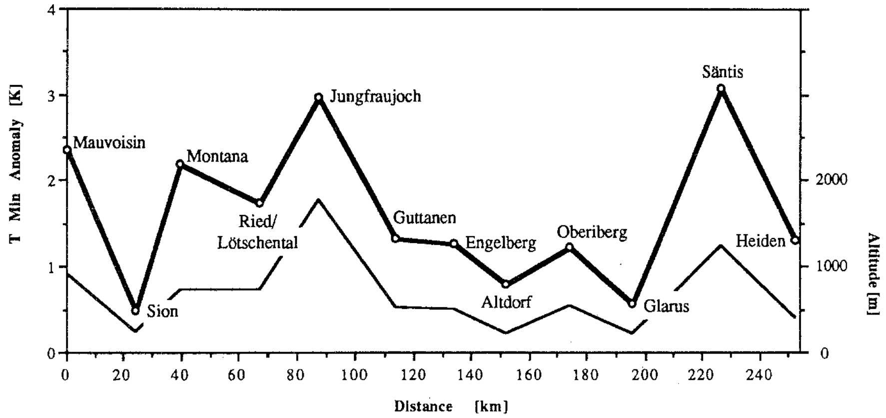

Fig. 11. As Fig. 10, but for the E-W transect illustrated in Fig. 1

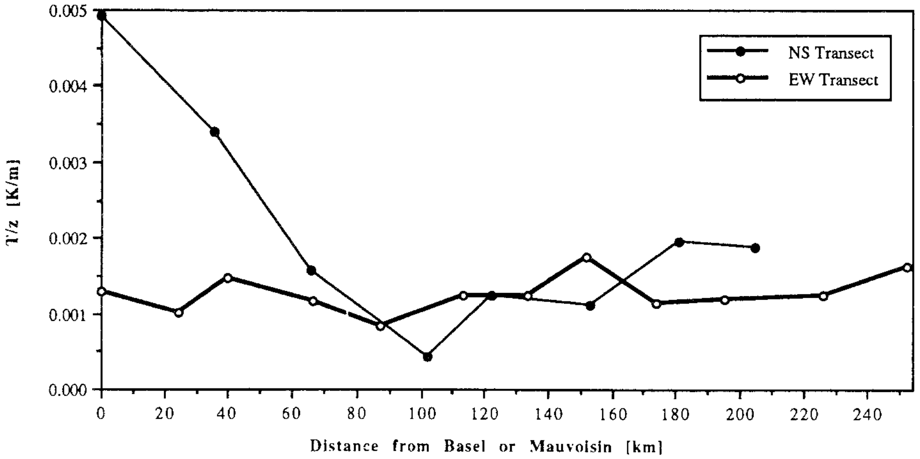

Fig. 12. Distribution of minimum temperature anomaly to altitude ratio along both the N-S and E-W transects as a means of highlighting regional differences in the data

time of the year, and to some extent latitude (in the case of the N-S transect). The deviations for the anomalously warm winters are not large along the E-W transect and reflect the relative homogeneity of the Alps as a region. There is little evidence of a significant continentality influence along these transects, as differences of the T/z ratio over this transect are relatively minor between one station and the next. For the N-S transect, on the other hand, the differences between Plateau locations (Basel and Wynau), which are frequently beneath fog and stratus clouds, and locations south of the Alps (Locarno and Lugano) not generally subject to persistant stratus, stand out clearly in this picture.

4. Conclusions

This paper describes an analysis of the temperature distribution in time and space in Switzerland over the 15-year period from 1979–1993, with a particular focus on temperature minima. It has been shown that both warm and cold winters exhibit minimum temperature anomalies which are height dependent. The study has allowed a quantification of the damping of climate signals, exemplified by the vertical temperature lapse rates, as an inverse function of elevation. This implies that high-elevation stations are more representative of free atmospheric conditions and are further removed from various contaminating effects characteristic of low elevations, such as topography and exposure of the measurement site. The study has also been able to distinguish the behavior of temperature anomalies in different climatological regions of Switzerland; each region exhibits a remarkable homogeneity of response to the climatic situation responsible for these anomalies, despite considerable differences in site conditions. The analysis of the anomalously warm and cold winters also provides a measure of the consistency of the definition of the Swiss climatological zones; the links between anomalies and altitudes are all very high in the Jura, Alps, and Southern Alps; the clustering of Plateau stations beneath winter stratus cover is also consistent with that particular region. In terms of the four criteria which Barry (1992) has put forth as determining mountain climates (see Section 1 of this paper), the altitudinal dependency is by far the most pronounced signal in the records of anomalous winters, followed by latitude (north and south of the Alps); continentality influences are not particularly visible for the chosen period. Topography as a measure of local site conditions also plays a role in the distribution of minimum temperature means and anomalies; this is particularly true for stations located on valley floors, where temperature inversions are likely to occur which decouple these stations from those above the inversion and closer to free atmosphere conditions.

The fact that there is a complete reversal of anomaly gradient between warm and cold winters, and that the range between cold and warm anomalies generally increases with height emphasizes the fact that high elevation sites are in a position to record with greater clarity and definition significant shifts in climate parameters on an interannual scale. This is also likely to be the case for longer-term climate change where possible signals of greenhouse-gas warming may be detected more clearly than at lower elevations; it is not unreasonable to expect that continuous and systematic observations at high elevation sites would provide the first tangible measurements of the warming trends which are projected by global climate models for coming decades. It is hoped that this kind of study, in the context of debates, controversies, and uncertainties related to anthropogenic climate change, may also have the effect of encouraging the continuing support for the operation and maintenance of high elevation observatory sites; a few of these century-long records have recently been discontinued for budgetary reasons (e.g., Dessens and Bucher, 1994).

Future studies will concentrate on the manner in which high-resolution climate models, both the global GCMs (General Circulation Models) and the regional LAMs (Limited Area Models) are capable of reproducing the altitudinal behavior of temperature anomalies in mountain regions, their damping out at lower elevations, and the switch of anomaly gradients between warm and cold periods. These mechanisms can have significant consequences for a number of climate-dependent systems in mountain regions, and their detailed study requires model-simulated inputs which reproduce the observed situation as accurately as possible.

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