Theor. Appl. Climatol. (2007)
DOI 10.1007/s00704-007-0296-2
Printed in The Netherlands

Theoretical and Applied Climatology

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Monthly air temperature trends in Switzerland 1901–2000 and 1975–2004

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With 5 Figures

Received August 8, 2006; revised December 28, 2006; accepted January 3, 2007
Published online June 27, 2007

Summary

We analysed long-term temperature trends based on 12 homogenised series of monthly temperature data in Switzerland at elevations between 316 m.a.s.l. and 2490 m.a.s.l for the 20th century (1901–2000) and for the last thirty years (1975–2004). Comparisons were made between these two periods, with changes standardised to decadal trends. Our results show mean decadal trends of +0.135 °C during the 20th century and +0.57 °C based on the last three decades only. These trends are more than twice as high as the averaged temperature trends in the Northern Hemisphere.

Most stations behave quite similarly, indicating that the increasing trends are linked to large-scale rather than local processes. Seasonal analyses show that the greatest temperature increase in the 1975–2004 period occurred during spring and summer whereas they were particularly weak in spring during the 20th century. Recent temperature increases are as much related to increases in maximum temperatures as to increases in minimum temperature, a trend that was not apparent in the 1901–2000 period. The different seasonal warming rates may have important consequences for vegetation, natural disasters, human health, and energy consumption, amongst others. The strong increase in summer temperatures helps to explain the accelerated glacier retreat in the Alps since 1980.

1. Introduction

Analysis of worldwide air temperature changes since the second part of the 19th century has shown that temperature has increased in both hemispheres and that most of the warming occurred during 1920–44 and after 1975 (Jones and Moberg, 2003; Luterbacher et al., 2004). During the latter period, warming in the Northern Hemisphere has been more than double that in the Southern Hemisphere (Jones and Moberg, 2003).

In Switzerland, the consequences of the warming trend have been visible in many natural phenomena, particularly those associated with the alpine character of the territory: in the retreat of glaciers (Paul et al., 2004), in decreased snowcover at elevations lower than 1300 m (Scherrer et al., 2004), in phyto-phenological trends (Defila and Clot, 2005), in altitudinal shifts of vegetation (Dobbertin et al., 2005; Walther et al., 2005), and in rapid changes in specific ecosystems (Rebetez and Dobbertin, 2004; Walther et al., 2005). The acceleration of glacier retreat, phyto-phenological trends and vegetation shifts since the mid 1980s has been particularly striking (Paul et al., 2004; Defila and Clot, 2005; Walther et al., 2005).

Temperature data in Switzerland have been shown to be of good quality and sufficient to enable detailed trend analyses at all elevations (e.g. Rebetez, 1996, 2001, 2004; Wanner et al., 1998; Schar et al., 2004). In addition to the minimum and maximum temperature data that have previously been used, MeteoSwiss has recently homogenised 12 mean temperature series from 1864 or 1901 to 2004 and in part has analysed long-term trends from 1864 to 2000 (Begert et al., 2005). These 12 stations are particularly interesting because they include both the northern and southern sides of the Alps and range from 316 m to 2490 m in altitude. The purpose of this paper is to analyse temperature trends during the 20^{th} century (1901–2000) and during the past 30 years (1975–2004) in order to compare these regional data sets with Northern Hemisphere and global values and to understand the seasonal geographical distribution of trends for the two periods under consideration. For model validation purposes and for the analysis of the consequences of temperature trends, the seasonal differences may be particularly important.

2. Data and methods

We used monthly mean temperature series recently homogenised for 12 stations in Switzerland (Begert et al., 2005). The mean temperature data used here are based on a tradition called "Mannheim hours" which was developed in Germany, Austria and Switzerland, and produces 3 daily temperature values (morning, afternoon and evening) instead of the usual maximum and minimum temperature data. Most of the inhomogeneities in the series were found in the 19^{th} century (i.e. in the part of the data not utilised in this study) and 93% of all inhomogeneities were explained by metadata (Begert et al., 2005). Here we use only 20^{th} and 21^{st} century data.

For comparison purposes, we used global, Northern and Southern Hemisphere temperature data from the Climatic Research Unit (HadCRUT2v), University of East Anglia,

Fig. 1. (**a**) Annual temperature anomalies [°C] in Switzerland compared to the Northern Hemisphere 1901–2004. (**b**) Slope of the decadal temperature trend [°C] based on a 30-year moving window

England. We also used minimum and maximum temperatures in Neuchatel (Switzerland) as well as mean temperatures for that station computed as the average value of minimum and maximum temperatures. We chose this site as its data are particularly reliable (Rebetez, 2001, 2004). Temporal comparisons were made between two periods: 1901–2000 and 1975–2004, with changes over these two periods being standardised to decadal trends.

We computed principal component and hierarchical cluster analyses using the Ward method on monthly temperature data. To explore whether some stations or months behave similarly or not and if a typology is possible, we used agglomerative hierarchical clustering (AHC) with Ward's method and a Euclidean distance matrix (Legendre and Legendre, 1998). Each sample is initially treated as a cluster and the method proceeds stepwise, systematically merging clusters whose fusion results in a minimum loss of information (i.e. there was a minimum increase in the total within-group error sum of squares).

3. Results

The mean annual warming trend in Switzerland (mean value for all stations) was 1.35 °C during the 20th century (1901–2000), but during the last 30 years (1975–2004) it increased to 0.57 °C per decade (this would mean a hypothetical centennial trend of 5.7 °C over the last three decades). The trends in annual temperatures for all individual stations are significant at the 99.9% significance level (Fisher's test). Swiss mean temperature trends (Fig. 1) were twice as high (factor of 2.05) as trends for global, Northern or Southern Hemisphere datasets (HadCRUT2v) over the 20th century (Table 1). Over the past 30 years, Swiss mean values were greater by a factor of 2.3 compared to the Northern Hemisphere average.

Table 1. Yearly linear temperature trends for Switzerland (12 stations) compared to the global, Northern and Southern Hemisphere datasets (HadCRUT2v), in °C decade^{-1}. All trends are significant at the 99% significance level

Series	1901–2000	1975–2004
Switzerland	0.135	0.571
Global	0.066	0.189
NH	0.065	0.250
SH	0.067	0.128

The slope of the trend (Fig. 1b) has been increasing constantly during recent decades. Even though there was also a strong increase during the 1930s and 1940s, with a maximum value during 1923–1952 (0.3 °C decade^{-1}), the slope of the 30-year increasing trend has consistently been steeper than that recorded over the 1963–1992 period. The absolute strongest trend was reached in 1974–2003 (0.58 °C decade^{-1}).

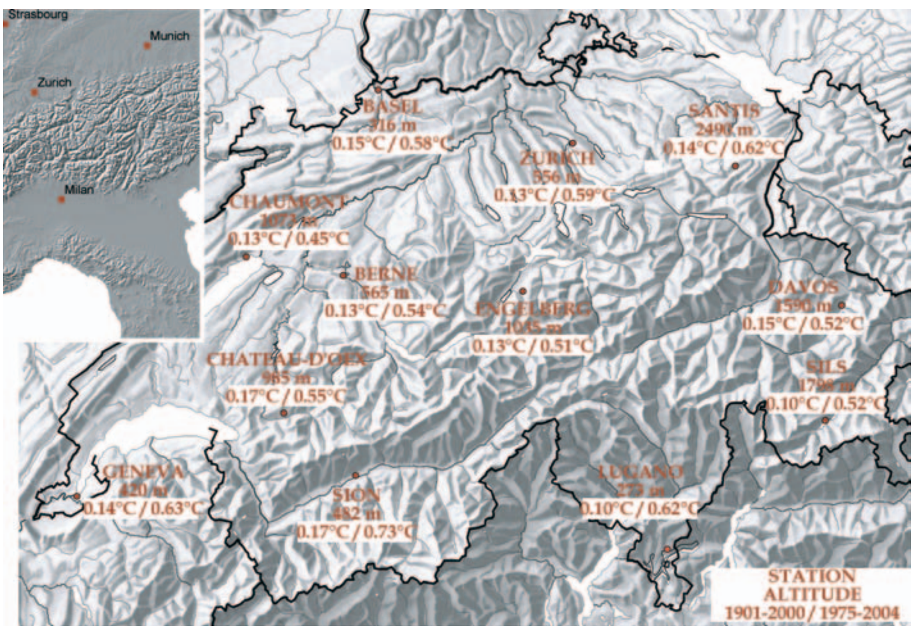

Fig. 2. Map of the stations with altitude and decadal trends for 1901–2000 (left) and 1975–2004 (right)

During the 20th century (1901–2000), the southern side of the Alps (Lugano and Sils) has warmed by 0.1 °C, compared to 0.13 to 0.16 °C in the north (Fig. 2). During the past 30 years, there was no difference between either side of the Alps. The decadal trends ranged from 0.45 to 0.73 °C for all stations on the northern side and from 0.52 to 0.62 °C on the southern side (Fig. 2). Over the past 30 years, below 1100 m.a.s.l., stations at lower elevations tended to have a more strongly increasing trend than those at higher elevations. This relationship, however, is not significant ($r = 0.51$ for 9 stations below 1100 m), and is reversed for the three stations above 1100 m.

When the decadal trends are calculated separately for each season, some distinct trends arise (Table 2). During the 20th century, spring temperatures have warmed by 0.1 °C per decade, and winter temperatures by 0.16 °C. Summer and autumn have warmed by 0.13 and 0.15 °C respectively per decade. Seasonal warming trends are all significant at the 95% significance level.

The hierarchical cluster analysis (Fig. 3, left) shows that the strongest gap in the monthly behaviour of the stations lies between the northern and the southern side of the Alps: Lugano and Sils, on the southern side, had distinct trends. Those on the northern side were quite similar, although a distinction is observed between most of the Alpine sites, on the one hand, and those in the Jura Mountains and Swiss Plateau on the other. The main difference between the two sides of the Alps concerns the lower values in the south for all months (Fig. 4). However, the general behaviour throughout the year was similar, with the same months having stronger or lower increasing trends.

Mean decadal seasonal trends during the period 1975–2004 ranged from +0.21 °C in autumn and 0.36 °C in winter to +0.86 °C in summer and 0.84 °C in autumn. Seasonal warming trends in

Table 2. Seasonal linear temperature trends for Switzerland (12 stations) in °C decade^{-1}

	1901–2000	1975–2004
DJF	**0.16****	0.38
MAM	0.10	**0.84****
JJA	**0.13****	**0.86****
SON	**0.15****	0.21
Year	**0.14****	**0.57****

* Significant at the 95% significance level
** Significant at the 99% significance level

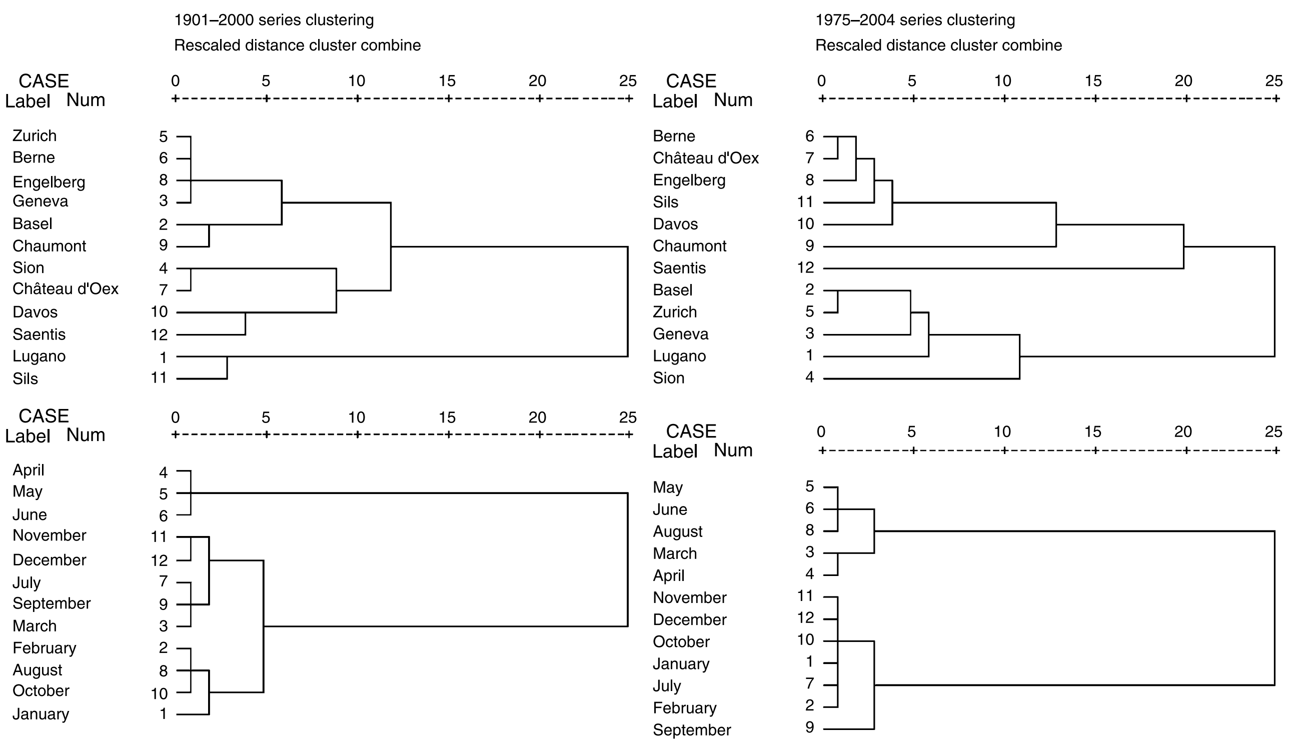

Fig. 3. Hierarchical cluster analysis using the Ward method for 1901–2000 (left) and 1975–2004 (right)

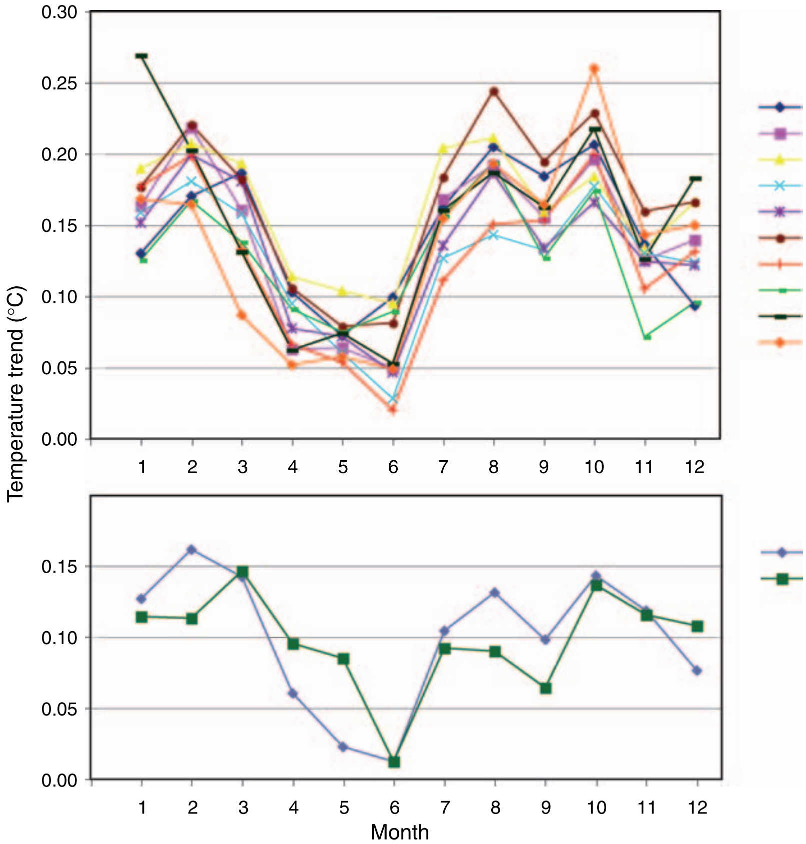

Fig. 4. Monthly decadal temperature trends [°C] on the northern (top) and southern (bottom) side of the Alps for 1901–2000

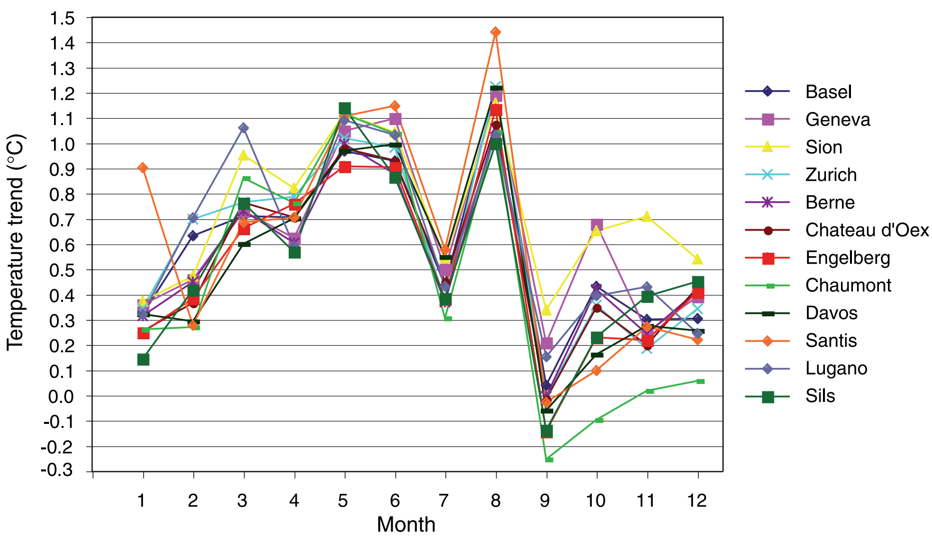

Fig. 5. Monthly decadal temperature trends [°C] for 1975–2004 for all stations

summer and autumn are significant at the 95% significance level.

As shown in Fig. 5, most stations behave quite similarly. The hierarchical cluster analysis (Fig. 3, right) shows a difference between most stations at lower and higher elevation.

Minimum and maximum temperature trends in Neuchatel (Table 3) show that the increase during 1901–2000 was mainly due to increasing minimum temperatures, which accounted for more than 80% of the yearly increasing trend. The minimum temperature trend is greater than the maximum temperature trend for each month. During 1975–2004, nearly half of the increasing trend could be accounted for by the maximum temperature increase.

Table 3. Seasonal linear temperature trends at Neuchatel (mean, minimum and maximum temperature) in °C decade^{-1}

	1901–2000			1975–2004		
	Mean T	Min T	Max T	Mean T	Min T	Max T
DJF	**0.19****	**0.26****	**0.12***	0.35	0.32	0.38
MAM	**0.13****	**0.23****	0.04	**0.69****	**0.63****	**0.75****
JJA	**0.15****	**0.28****	0.02	**0.65****	**0.73****	**0.58***
SON	**0.16***	**0.26****	0.07	0.03	0.16	−0.09
Year	**0.16****	**0.26****	**0.6***	**0.43****	**0.46****	**0.40****

* Significant at the 95% significance level
** Significant at the 99% significance level

During 1901–2000, lower trends in spring were mainly due to small or even decreasing trends in maximum temperature. The greatly increasing trends in spring in the period 1975–2004 were due to increases in both minimum and maximum temperature.

4. Discussion

Our results show that increasing annual temperature trends in Switzerland have been approximately twice as large as the mean trends for the Northern Hemisphere during both study periods, with a slightly stronger difference during the most recent period: 2.05 times greater increase in Switzerland for 1901–2000 and 2.3 times greater for 1975–2004. The difference between the Swiss trends and those for the mean Northern Hemisphere is not surprising taking into account the latitude (47° N) and continentality of the study region, as warming rates are expected to increase with distance from the coast and with latitude (Hanssen-Bauer et al., 2005; Cai, 2006).

The rate of increase was much greater in 1975–2004 than for the 1901–2000 period. In considering impacts, the greatest acceptable threshold is usually considered to be 2 °C above pre-industrial temperatures or a 2 °C centennial increasing trend (Schneider, 2001; Grassl et al., 2003; Hare, 2003; Dessai et al., 2004; Mastrandrea and Schneider, 2004). Over the last 30 years the trend in the Northern Hemisphere (+0.25 °C per decade) has exceeded this maximum limit. In Switzerland, the trend (+0.57 °C per decade) is far in excess of this limit. Given that the 'short-term' recent period now equates to the standard 30-year period used in climate data series analysis, thus trend needs to be taken seriously.

Our analysis shows high agreement between stations, indicating that synoptic factors may dominate over station-based factors: the observed trends indicate a general warming at all sites and cannot be related to locally changing conditions alone. In the 1975–2004 period, there was no difference between the northern and southern side of the Alps, despite these two regions usually having different weather conditions due to the barrier effect of the Alps on air masses crossing the continent.

The fact that, over the past 30 years, stations at lower elevation have revealed a more strongly increasing trend than those at higher elevation only concerns altitudes below 1100 m.a.s.l. Above this threshold, trends are increasing more strongly, in agreement with the general understanding that mountainous regions tend to warm more rapidly (Bradley et al., 2004, 2006). We suspect that the different warming rates below 1100 m.a.s.l. in our series may be influenced more by topography than by elevation as all these stations, except Santis, lie in different types of valleys. The number of stations, though, is too small to calculate robust correlations. The impact of elevation should ideally be calculated based on free atmosphere data.

During the 20th century, the seasons warming most rapidly were winter and summer, while the rates of temperature increase in spring were the least important and not significant. In marked contrast, over the last three decades (1975–2004), temperatures have increased most in spring and summer and least in autumn and winter. The exceptionally high temperatures in summer 2003 in Europe contributed to the remarkable increase during this season, but the trend would also be strong without that year: +0.70 °C per decade until 2002. The stronger increases in spring and summer during the last decades compared to the 20th century means that the vegetation period has been impacted more by warming in recent decades than during the remainder of the century. The strong increase in summer temperatures helps to explain the accelerated glacier retreat in the Alps since 1980 described by Paul et al. (2004).

Minimum and maximum temperature analyses in Neuchatel indicate that the dominant impact of minimum temperature trends during the period 1901–2000 compared to maximum temperature trends does not appear in the 1975–2004 series. Night and day temperatures have increased by approximately the same proportions over the last three decades. This confirms that the increase in aerosols during the 20th century, which is considered to have caused the dichotomy between minimum and maximum temperature trends (i.e. the decrease in daily temperature range (Katz and Brown, 1992; Hansen et al., 1995; Rebetez, 1998, 2001)), has not impacted temperature increases over the last three decades (Wild et al., 2004, 2005). The substantial increase in temperature during the last 30 years is due to increases in both minimum and maximum temperatures. This is particularly so during the seasons with the greatest rates of temperature increase, spring and summer. Aerosols associated with air pollution also appear to have had an impact on the absolute mean temperature trend values during the 20th century. This has reduced the impact of the greenhouse gas radiative forcing, particularly from the 1950s to the 1970s (Hansen et al., 1997; Bellouin et al., 2005) and explains, in part, the greater temperature increase during the 1975–2004 period compared to 1901–2000. The greater rate of temperature increase in spring during the recent period could also be partly explained by snow and ice melt in the Northern Hemisphere (Hansen and Nazarenko, 2004).

Based on a commonly used wet adiabatic lapse rate, i.e. a theoretical altitudinal gradient of 0.5 °C/100 m (lower atmosphere) for the snowfall/rain limit, our results suggest that since 1975, the lowest altitude that snow will fall has increased by +200 m between December and January, +250 m in February, +450 m in March and +400 m in April. This may have important economic impacts in the Alps as winter sports have a strong economic value in the whole region and in Switzerland in particular.

5. Conclusions

Our analysis of 12 monthly temperature data series in Switzerland, each more than 100 years long, has revealed that the decadal rate of temperature increase has reached 0.135 °C during the 20th century and 0.57 °C during the past 30 years (1975–2004). The temperature increases currently being experienced in Switzerland are nearly three times higher than the level currently considered as acceptable i.e. a 2 °C century^{-1} temperature increase.

The similarity in the behaviour of the 12 Swiss stations included in the analysis, despite their very different geographic locations on both sides of the Alps, particularly during the last three decades, indicates that the observed trends are due to a general, or at least a regional, warming and not to local conditions.

Over the last three decades (1975–2004), temperatures have increased most in spring and summer and least in autumn, whereas during the 20th century (1901–2000), the seasons warming most rapidly were winter and summer, while trends in spring were lowest. These differentiated warming patterns may have important impacts on vegetation, natural disasters, human health, and energy consumption amongst others. In particular, the strong warming rate in summer is an important explanation for the increasing glacier retreat since the 1980s. We suggest that future analyses of impacts of climate change should take into account differentiated seasonal temperature trends. The theoretical (0.5 °C/100 m) increase in the lower altitude of snowfall since 1975 corresponds to 350 m on a yearly basis, but only to 230 m in winter or, in contrast, to 500 m in spring.

Compared to trends during the 20th century, in which the role of minimum temperatures was preponderant, the rates of temperature increase from 1975 to 2004 indicate that night- and daytime temperatures now contribute to the increases by approximately the same extent, particularly during the seasons when the warming has been greatest, i.e. spring and summer. We suggest that this is due to a reduction in the impact of aerosols associated with pollution. The effect has been greatest on maximum temperatures. The observed reduction of snow and ice cover may have contributed to the remarkable increase in recent spring temperatures and to the greater increase in Swiss or Alpine temperatures compared to mean values for the Northern Hemisphere.

Future research should concentrate on the analysis of other climatic and other environmental parameters. Our analysis clearly shows very strong rates of temperature increase in Switzerland during the last decades. Parameters likely to be influenced by temperature are expected to show important changes during this period, particularly those related to maximum, to spring and to summer temperature, as these have increased most during recent decades compared to the rest of the century.

Acknowledgements

We are grateful to MeteoSwiss for providing the climatological data and to John Innes for useful comments and suggestions. This work has been supported in part by the Forest Investigation Program, a joint project between the Swiss Federal Office of the Environment (BAFU) and the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL).

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