Vol. 27: 45–50, 2004 | CLIMATE RESEARCH Clim Res | Published August 4

Summer 2003 maximum and minimum daily temperatures over a 3300 m altitudinal range in the Alps

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ABSTRACT: The summer of 2003 was extremely hot in Western Europe and in the Alps. Here I analyse the role of elevation in the temperatures measured in 2003, and I compare daytime and nighttime values. Records from 16 stations at varying elevations show that, during the night, there was a significant correlation between heat and altitude. Hot nighttime temperatures were particularly frequent at low elevation. The frequency of unusually hot daytime highs was not correlated with altitude, but with the average degree of insolation of the sites. Compared to long-term averaged values (1961–1990) the temperatures were hottest in the normally sunniest sites. The unusual nature of the 2003 heat wave was not the absolute daily extreme values, but the lack of cool temperatures and the large number of very warm days. Averaged over all climate stations, half of the days in summer were hotter than the 90th percentile (climate normals 1961–1990), with up to 72% at some stations.

KEY WORDS: Climate change · Temperature · Altitudinal range · Switzerland · European Alps · Global warming · Elevation gradient · Summer 2003

1. INTRODUCTION

Summer 2003 was extremely hot in western Europe. Analysing the period since 1500, Luterbacher et al. (2004) report that 2003 was by far the hottest summer since 1500. This event took place in a general warming trend over the 20th and early 21st century. The European climate is now warmer than that of any time during the past 500 yr (Luterbacher et al. 2004). Schär et al. (2004) showed that an event such as the heat wave measured over Europe in summer 2003 was statistically extremely unlikely, even when the observed warming trend was taken into account: the mean summer (June–August) temperature for 2003 exceeded the mean summer temperature for the period 1961–1990 by more than 3°C over an area ranging from Spain to Hungary and from Iceland to Greece, an excess of up to 5 standard deviations (SD) from the mean. The hottest region relative to long-term climate normals was centered over the European Alps and Switzerland. The average value of 4 low-elevation (316–570 m above sea level, masl) stations in Switzerland showed that not only the summer mean (+5.4 SD) but also the months of June (+5.3 SD) and of August (+4.1 SD) considered separately were by far the hottest ever measured, while July (+1.8 SD), although not record-breaking, was also hot (Schär et al. 2004).

In the context of climatic change, extremes are very important (Katz & Brown 1992). Extreme temperatures are often more interesting than mean monthly or seasonal temperatures (Folland et al. 1999, Zhang et al. 2001). This holds true both for human perception (e.g. Rebetez 1996) and socio-economic impacts (e.g. Burroughs 1997, Meehl et al. 2000, IPCC 2002), as well as ecological impacts such as on vegetation, wildlife or stone falls (e.g. Rebetez et al. 1997, IPCC 2002). Changes in extremes are not necessarily parallel to changes in means, and the cooler part of temperature distributions often increases more than the warmer part (e.g. Karl et al. 1993, Jones et al. 1999, Meehl et al. 2000, Rebetez 2001, IPCC 2002). A stronger increase in minimum temperatures at lower elevation sites has been shown to be at least partly linked to changes in insolation (Hansen et al. 1995, 1997a,b, Rebetez & Beniston 1998): a decrease in the diurnal temperature

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range (DTR) is associated with a corresponding increase in low-level cloudiness, possibly due to anthropogenic aerosols.

Percentiles are useful in the analysis of extreme temperature values if we want to extend the results to other regions and to allow for a comparison between different elevations (Folland et al. 1999, Zhang et al. 2001). Switzerland is a good place for an analysis of temperature extremes in general (Heino et al. 1999), and for summer 2003 in particular (Schär et al. 2004), because long series of good quality data are available for low-, mid- and high-elevation stations (Heino et al. 1999, Rebetez 2001, Schär et al. 2004).

In this paper, we define 'extreme days' and analyze their occurrence in 2003 at different elevations using various thresholds. Through the analysis of daily extreme values, we contribute to the understanding of how temperatures were distributed during summer 2003, and we show increasing trends in the number of extreme days since the beginning of the 20th century.

2. DATA AND METHODS

We analyzed different percentile thresholds (80, 90 and 95, as well as 20, 10 and 5) for daily minimum and maximum temperature data in June, July and August (JJA). We compared 2003 to 1961–1990 for 16 meteorological stations with altitudes ranging from 197 to 3580 masl. Their geographical distribution can be viewed in Fig. 1 and their altitudes in Table 1. For 2 stations, one at low elevation and the other at high elevation, we compared the temperatures of summer 2003 with those of 1901–2002, analyzing centennial trends. We also compared the temperature distribution of summer 2003 with other remarkably hot summers of the century. All the data originate from the Swiss meteorological database by MeteoSwiss.

3. RESULTS

The number of extreme days in summer 2003 for the 3 percentile thresholds based on the 1961–1990 reference period are summarized in Table 1. During summer 2003, 1 day out of 2, on average, had temperatures higher than the 90th percentile threshold, for both minimum and maximum temperatures. 66 % of the days were warmer than the 80th percentile and 34 % warmer than the 95th percentile.

On the other side of the distribution, no single day for any on the 16 observed sites exhibited a minimum temperature lower than the 10th percentile. Only 7 stations had up to 2 days with a minimum temperature

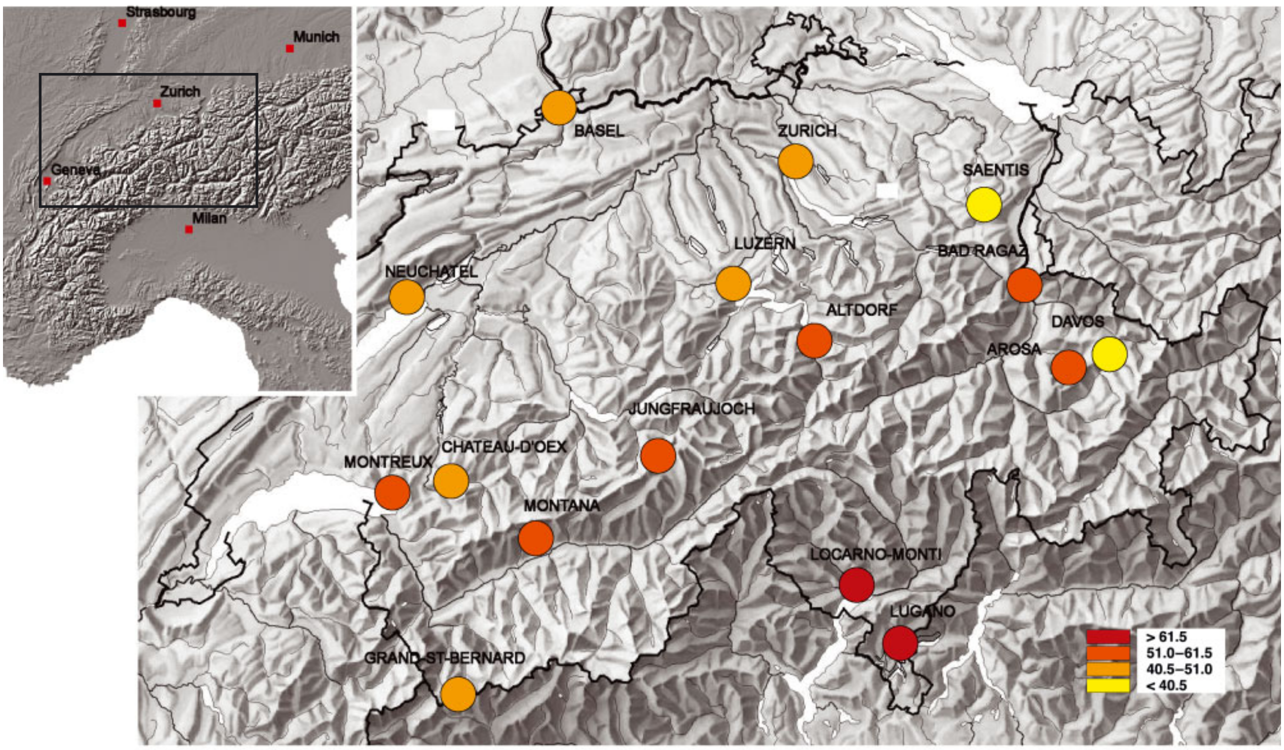

Fig. 1. Map of Switzerland and number of days in summer 2003 which exceeded the 90th percentile for the 1961–1990 maximum temperature. The sunniest stations have the largest number of extreme days

Table 1. Frequency (%) of days in summer 2003 higher than the 80th, 90th or 95th percentiles (1961–1990 reference) for minimum (T_{min}) and maximum (T_{max}) temperature and for 16 stations in Switzerland at various elevations. masl: m above sea level

Station	Altitude (masl)	T_{min} 80th	T_{min} 90th	T_{min} 95th	T_{max} 80th	T_{max} 90th	T_{max} 95th
Locarno-Monti	197	71.7	56.5	46.7	78.3	71.7	65.2
Lugano	273	78.3	59.0	43.5	68.5	62.0	48.9
Bale	316	65.2	54.3	46.7	68.5	46.7	29.3
Montreux	405	75.0	58.7	42.4	66.3	55.4	39.1
Altdorf	449	70.7	55.4	31.5	70.7	58.7	42.4
Luzern	465	66.3	44.6	29.3	62.0	44.6	28.3
Neuchatel	485	70.7	56.5	35.9	70.7	47.8	31.5
Bad Ragaz	496	68.5	56.5	43.5	71.7	52.2	38.0
Zurich	556	71.7	54.3	39.1	65.2	41.3	29.3
Chateau-d'Oex	985	63.0	42.4	26.1	62.0	44.6	31.5
Montana	1508	56.5	39.1	23.9	69.6	53.3	38.0
Davos	1590	57.6	43.5	30.4	50.0	38.0	29.3
Arosa	1840	69.6	46.7	33.7	68.5	52.2	43.5
Grand-St-Bernard	2472	48.9	34.8	22.8	55.4	41.3	29.3
Saentis	2490	60.9	41.3	21.7	53.3	40.2	27.2
Jungfraujoch	3580	54.3	38.0	22.8	68.5	55.4	44.6
Average		65.6	48.9	33.8	65.6	50.3	37.2

below the 20th percentile. For maximum temperature, there was no station with a value below the 5th percentile, 4 stations with 1 day below the 10th percentile, and 12 stations with up to 3 days below the 20th percentile.

The minimum temperatures of summer 2003 show particularly high ranks at lower elevations. For all thresholds (80th, 90th and 95th percentiles), there is a highly significant trend ($p < 0.001$) towards more frequent occurrences at a lower elevation. That is, more warm nights occurred at low compared with high elevation. For example, a fitted trend (regression) line shows that 55.2 % of the summer days in 2003 are estimated to be higher than the 90th percentile of the 1961–1990 reference period at an altitude of 200 masl, with a decrease of 6.8 % per 1000 m of altitude (i.e. 48.4 % at 1200 masl or 34.8 % at 3200 masl).

The geographical distribution of maximum temperature departures in 2003 (Fig. 1) first appears to correspond to higher temperatures on the southern side of the Alps and in the alpine region, with lower values on the Plateau and the Jura foothills, but there are actually some strong dichotomies between nearby sites. There is no significant correlation between maximum temperatures and altitude, although the slight trends in these data are always negative (as for minimum temperatures). However, there is a significant ($p < 0.02$ to $p < 0.1$) positive correlation between summer 2003 maximum-temperature departures and the mean duration of insolation in summer for the 1961–1990 reference period (Table 2), for both absolute and relative sunshine duration (absolute = hours, relative = percent of effective compared to possible duration according to topography, latitude and time of the year). The sunniest places experienced particularly hot afternoon temperatures during summer 2003. For minimum temperatures, the correlation with sunshine duration is never significant, although it is consistently positive.

Based on the values for the whole 20th century (Table 3), a higher number of warm minimum temperatures occurred at low elevation in 2003 compared with maximum temperatures. At higher elevation, the pattern of differences between minimum and maximum temperatures is very small and not consistent.

Centennial trends are reported in Table 4. The average number

Table 2. Correlation coefficient (r) between sunshine duration and maximum temperature anomalies for 16 stations for different percentile thresholds

	80th	90th	95th
Absolute sunshine duration	0.5460	0.4616	0.4058
Relative sunshine duration	0.4511	0.5324	0.4925

Table 3. Frequency (%) of summer days in 2003 higher than the 80th, 90th or 95th percentiles (1901–2002 reference) for minimum (T_{min}) and maximum (T_{max}) temperature at low and high elevations

Station	Altitude	Parameter	80th	90th	95th
Neuchatel	485	T_{min}	80.4	60	39
Neuchatel	485	T_{max}	74	47	30
Saentis	2490	T_{min}	62	38	22
Saentis	2490	T_{max}	53	40	27

Table 4. Centennial increase in the expected number of summer days warmer than the 80th, 90th or 95th percentiles (1901–2002 reference) for minimum (T_{min}) and maximum (T_{max}) temperatures at low and high elevations

Station	Altitude	Parameter	80th	90th	95th
Neuchatel	485	T_{min}	34	22	13
Neuchatel	485	T_{max}	5	2	0
Saentis	2490	T_{min}	13	9	13
Saentis	2490	T_{max}	14	10	6

of hot days over the last century (Fig. 2) has increased so strongly that the hottest summers at the beginning of the 20th century were similar to the coolest at the beginning of the 21st century. For Neuchatel (Fig. 2), the record value is clearly 2003, with 74 days hotter than the 80th percentile, but, since the 1990s, earlier peaks occurred in 1994 (59 days), 1995 (49 days) and in 1991 (46 days). In contrast, in 1900, only 2 days in the summer were expected to be so hot and no more than 20 hot days occurred in one summer during the first 2 decades. Now, at the beginning of the 21st century, 36 days are expected to be hotter. The 74 days of 2003 is twice the present expected value, clearly a high figure, but it would have been completely unrealistic at the beginning of the 20th century.

A comparision of the distribution of the maximum daily temperatures in 2003 to those of the whole century and of the other very hot years (Fig. 3) shows that 2003 did not exhibit the highest recorded temperature. 1921 and 1947 had some hotter days. The corresponding cumulative frequencies (Fig. 4) illustrate how summer 2003 differed from the average summers of 1901–2002, and also from the other previous hot summers, with a clear lack of cool days. During the other very hot summers, at least 20% of the days had a maximum temperature of less than 22°C, whereas only 7% were below this threshold in 2003. But if we consider the number of days above 32°C, 2003 becomes similar to the other hot summers of the century.

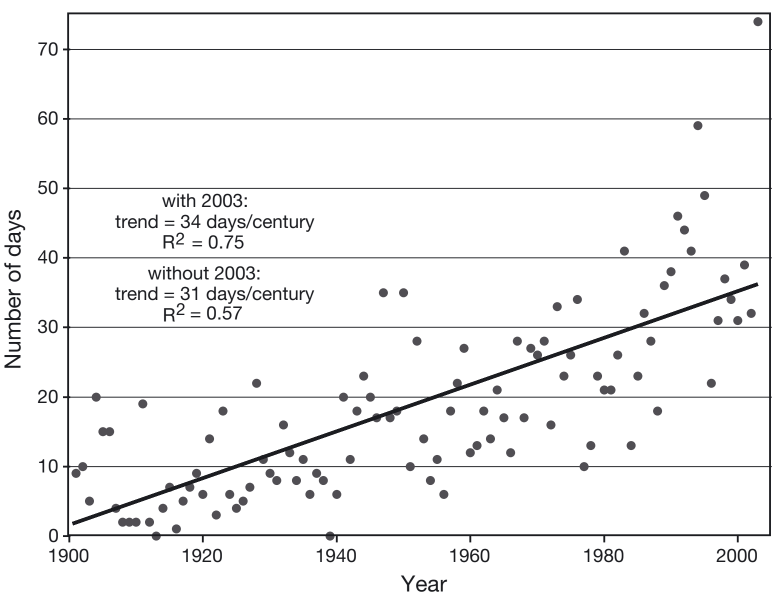

Fig. 2. Number of days with minimum temperature above the 80th percentile at low elevation (Neuchatel), 1901–2003

4. DISCUSSION

Our analyses of the Swiss data show that, compared with other hot summers of the century, summer 2003 had a large number of very warm minimum or maximum temperatures, although no daily maximum was the highest recorded. Summer 2003 also lacked cool days.

Nights were particularly warm at lower elevations. Our hypothesis is that, in a mountainous terrain, this is due to restrictions on air exchange at a lower altitude, such as in a valley bottom, in contrast to air movements in a pass or near a mountain summit. This would not be the case in winter, as cold air accumulates in the valleys during the night. But in summer, when the nights are much shorter than the days, the cooling possibilities in the valleys are restricted as long as no new cooler air mass is forced.

The stations exposed to the longest sunshine duration exhibit particularly high maximum temperatures compared to their normal average values. During this long warm summer, the afternoon temperatures were highest at the sites most exposed to sunshine. Long sunny days allowed hotter maximum temperatures where the insolation lasted longer compared to shadier sites. In otherwise similar sites, temperatures are expected to become higher during the day at sites where the exposure to sunshine is longer. This might occur where a mountain hides one site from the sun during part of the day, for instance. In contrast, during the following night, the cooling capacities are not very different between these 2 hypothetical sites, although our results show that there is also a small, but clearly non significant, relationship between insolation and minimum temperature. This small effect is probably due to the impact of the temperature of the previous day on that of the following night.

The global temperature increase since the beginning of the 20th century means that the values observed during summer 2003 were not as extreme in terms of being an outlier as they would have been 100 yr earlier. Other summers during the 1990s, (e.g. 1991, 1994 and 1995) also showed long series of very warm days and nights. Still, the number of hot days or nights reached in 2003 was clearly record-breaking. The number of warm minimum temperature values at lower elevations, for instance, was still twice the present expected figure.

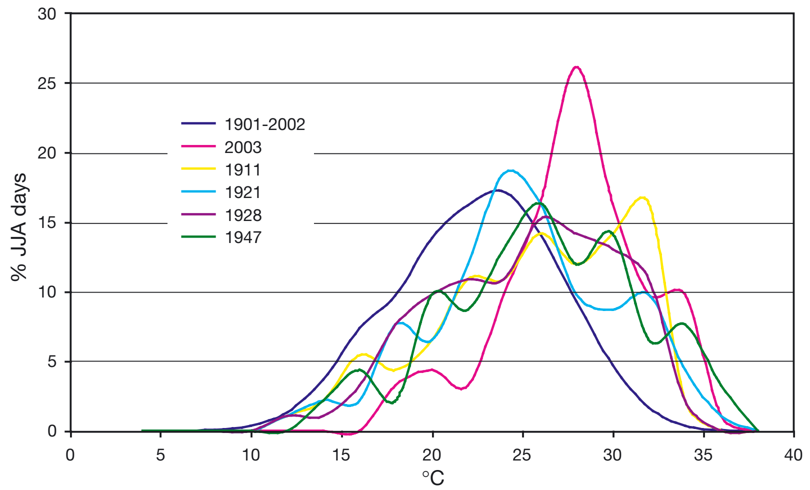

Fig. 3. Distribution of daily maximum temperatures in 2003 compared to climate normal 1901–2002 and to selected hot summers (with highest number of days >95th percentile). June-July-August (JJA) temperatures at low elevation (Neuchatel)

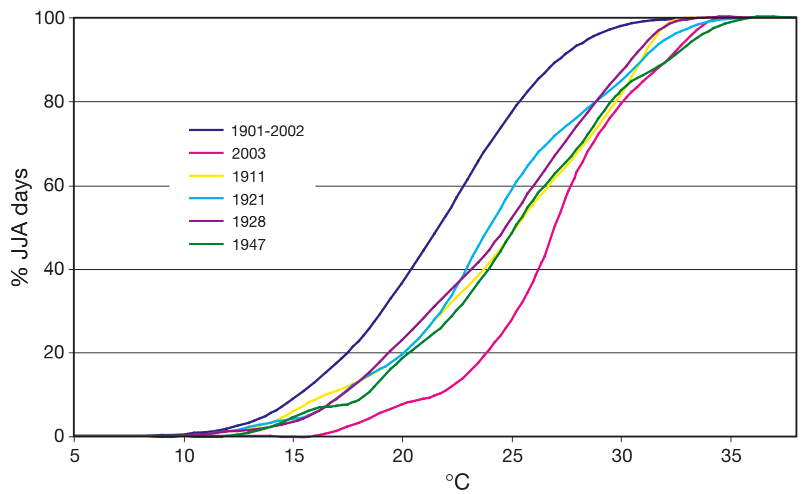

Fig. 4. Cumulative frequencies of daily maximum temperatures in summer 2003 compared to climate normal 1901–2002 and to selected hot summers (same data as Fig. 3)

5. CONCLUSION

Temperatures in summer 2003 were extremely high in terms of both mean values and extremes. Our analysis of minimum and maximum temperatures for 16 sites in Switzerland shows that the temperature increase compared with long-term (1961–1990) average values was not spatially homogenous. Minimum temperatures were particularly warm at lower elevations, whereas maximum temperatures were highest at the sunniest sites. We suggest that this is due to the fact that on plains and in valleys, night cooling was less efficient than it was at higher stations in the mountains. Daytime highs were most extreme in the stations most exposed to sunshine, probably due to longer sunny days compared with shadier sites.

Compared with normal summers, a large number of the days and nights during summer 2003 were warmer than expected. For the 16 sites analysed here, 1 day out of 2, on average, exhibited temperatures higher than the long-term 90th percentile and less than 4 % were below the 20th percentile.

Hotter summer days have occurred previously; 2003 did not necessarily exhibit record highest temperatures. Moreover, the number of hot days (above the 90th percentile) has clearly increased since the beginning of the 20th century, and some summers during the 1990s also experienced frequent hot days or nights, which makes the 2003 temperatures appear less exceptional now than they would have in the past. Still, the number of hot days and nights was clearly extreme in summer 2003 compared to what could be expected, even in the context of the 21st century.

Acknowledgements. This work has been supported in part by the Forest Investigation Program, a joint project between the Swiss Federal Office of the Environment, Forests and Landscape (BUWAL, Bern) and the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL, Birmensdorf). We are grateful to MeteoSwiss for providing the climatological data; to S. Attinger and L. Bernhard for their help with the map in Fig. 1; and to M. Reinhard and F. Gadallah for their positive and constructive comments.

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Editorial responsibility: Helmut Mayer, Freiburg, Germany

Submitted: April 2, 2004; Accepted: May 20, 2004
Proofs received from author(s): June 30, 2004