

## **The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations**

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### **Abstract**

The 2003 heat wave that affected much of Europe from June to September bears a close resemblance to what many regional climate models are projecting for summers in the latter part of the 21<sup>st</sup> century. Model results suggest that under enhanced atmospheric greenhouse-gas concentrations, summer temperatures are likely to increase by over 4°C on average, with a corresponding increase in the frequency of severe heat waves. Statistical features of the 2003 heat wave for the Swiss site of Basel are investigated and compared to both past, 20<sup>th</sup> century events and possible future extreme temperatures based on model simulations of climatic change. For many purposes, the 2003 event can be used as an analog of future summers in coming decades in climate impacts and policy studies.

### **Introduction**

The record heat wave that affected many parts of Europe during the course of summer 2003 has been seen by many as a “shape of things to come”, reflecting the extremes of temperature that summers are projected to occur in the later decades of the 21<sup>st</sup> century. The heat wave also affected Switzerland to the extent that previous records for summer maximum temperatures observed in the late 1940s and early 1950s were broken in many locations in August, 2003, according to the Swiss weather service. Research by Pfister et al. (1999), indeed suggest that 2003 is likely to have been the warmest summer since 1540. Climate reconstructions, based on written historical archives, for that particular summer suggest that Europe was under the influence of a strong high pressure system centered on the English Channel that resulted in prolonged drought and heat throughout much of that year. Many rivers ran dry by the end of the summer, and crops that had started growing 3-4 weeks earlier than normal wilted prior to harvest, leading to dire conditions for many communities.

This paper places the 2003 heat wave in the perspective of century-scale climatic fluctuations that have occurred during the 20<sup>th</sup> century and are expected to take place in the 21<sup>st</sup> century as climate responds to enhanced atmospheric content of greenhouse gases. Trends since 1900 are assessed on the basis of data from the Swiss climate observation network (Bantle, 1989), and information on future shifts in means and extremes of summer temperatures are based on regional climate model simulations undertaken in the context of a major EU project (PRUDENCE; Christensen et al., 2002).

### **Data**

There is a reasonable degree of confidence in the quality of climatological data for a number of Swiss locations, as the daily data has been homogenized for numerous sites such as Zurich, Bern, Neuchâtel or Geneva (Begert et al., 2003), and is accessible in many instances in digital form since 1901. Within the European Union project PRUDENCE (EVK2-CT-2100-00132), a suite of regional climate models have been applied to the investigation of climatic change over Europe for the last 30 years of the 21<sup>st</sup> century, enabling changes in a number of key climate variables to be assessed. When analyzing the results for temperature in Europe, the different model simulations broadly agree on the magnitude of change in mean, maximum, and minimum temperatures; Deque (2003) has highlighted the clustering of model results that constitutes one measure of the uncertainty or reliability of the regional-scale simulations. The HIRHAM4 regional climate model (RCM) of the Danish Meteorological Institute (Christensen et al., 1998) is one such model whose results correspond well with those of the other RCMs used in PRUDENCE. Furthermore, simulations of the reference climatic period 1961-1990 has shown that HIRHAM4 exhibits skill in reproducing contemporary climate, thereby providing some confidence as to its capability for simulating the characteristics of temperatures in the future. The model operates at a 50-km resolution and has completed two thirty-year simulations, i.e., “current climate” or the “control simulation” for the period 1961-1990, and the future “greenhouse-gas climate” for the period 2071-2100. Of the range of possible emission scenarios, only results based on the IPCC SRES A2 scenario (Nakicenovic et al., 2000) are discussed

here; A2 assumes a high level of emissions in the course of the 21<sup>st</sup> century, resulting from low priorities on greenhouse-gas abatement strategies and high population growth in the developing world. The A2 scenario leads to atmospheric CO<sub>2</sub> levels of about 800 ppmv by 2100 (three times their pre-industrial values) and provides an estimate of the upper bound of climate futures discussed by the IPCC (2001). The fully-coupled ocean-atmosphere general circulation model (GCM) of the UK Hadley Centre, HADCM3 (Johns et al., 2003) has been used to drive the higher-resolution atmospheric HadAM3H model (Pope et al., 2000), that in turn provides the initial and boundary conditions for the RCMs used in the PRUDENCE project, including HIRHAM4.

This study reports on trends in daily summer maximum temperatures averaged over the three summer months (June-July-August means; hereafter referred to as summer Tmax) at Basel located at 367 m above sea-level, in the north-western part of Switzerland close to the French and German borders, and the upper extreme of the probability density function of temperature that has direct relevance for the investigation of heat waves such as the 2003 event.

## Results

Figure 1 illustrates the anomalies of summer Tmax recorded each year from 1901-2003, computed as departures from the 1961-1990 climatological average period. The 2003 event clearly stands out as the record-breaking summer since 1901, with positive Tmax anomalies as high as 6°C in Basel (1°C higher than the previous record of 1947).

An analysis of threshold exceedance, however, reveals that summer Tmax in Basel exceeded the 30°C threshold fewer times in 2003 (41) than in 1947 (49), for example, as seen in Figure 2. This particular threshold was chosen because it defines the 90% quantile of summer Tmax at this location, and thus any excess beyond 30°C corresponds to the extreme high tail of probability density function of maximum summer temperature as defined by the IPCC (2001). In terms of persistence, there were 12 consecutive days in 2003 during which Tmax exceeded 30°C as opposed to 16 in 1976 and 14 in 1947. The 1940s stand out as a decade in which a clustering of summers with a threshold excess of 20 days or more is not uncommon, whereas such events tend to diminish in the 1970s and 1980s. According to the statistics considered, therefore, 2003 is not seen to have broken all records in terms of extremes; the sudden jump to high exceedance values following over a quarter century where summers never exceeded the 30°C threshold for 20 days or more does, however, constitute a “climatic surprise”.

Results from simulations with the HIRHAM4 RCM for the A2 emissions scenario, show a strong warming over much of Europe. Figure 3a highlights the change in mean summer Tmax that intervenes between the reference years 1961-1990 and the future period 2071-2100. The change in summer temperatures follows a generally zonal pattern, implying a northward shift of current climatic zones. A general increase of summer temperatures of about 4°C is observed in a band stretching from the Atlantic across Central Europe to the Black Sea. Stronger increases (6°C) occur over the Iberian Peninsula and the south-western parts of France, in part because of a probable reduction of soil moisture related to a simultaneous increase in summer drought (e.g., Christensen and Christensen, 2003) and the positive feedback that this induces in terms of low-level atmospheric temperatures, as shown previously for the alpine region by Rotach et al. (1997). Figure 3b shows changes in the 90% quantile of summer maxima, and here a stronger shift in temperatures is observed for south-western Europe, eastern Europe and on into the Ukraine and Turkey, as well as in the Baltic. The RCM simulations indicate that for many locations, there will be an asymmetric shift in extremes as mean summer Tmax increase, i.e., a 5°C average warming may be accompanied by a 6-8°C increase in the upper extreme of temperature, as seen in south-west France, for example. In other parts of the continent, the asymmetry between changes in means and in extremes is much less pronounced, as in the alpine domain north of Italy in particular. The simulated asymmetry in certain areas of Europe is partly the result of differential changes in trends of mean and extreme temperatures between 2071 and 2100. These differential trends can be explained by non-linear feedbacks linked to soil moisture deficits in some areas and to changes in cloudiness in other areas. Figure 3c illustrates the change in threshold exceedance beyond the 30°C limit between current and future climates. The increase in the number of hot days is most pronounced in the Mediterranean zone and Eastern Europe, with an additional 60 days or more above 30°C than under current climatic conditions; elsewhere in Europe, however, there is also a substantial increase in threshold exceedance up to about the 55<sup>th</sup> parallel.

## Discussion

A comparison between the HIRHAM4 statistics and data from Switzerland shows that there is a remarkable overlap of the cumulative probability density functions (PDF) of observed summer Tmax in Basel for the 1961-1990 period and as simulated for the closest grid-area to Basel in the RCM (Figure 4). Under future climatic conditions (2071-2100), mean JJA Tmax increases by 5.2°C at Basel, from 23.6°C to 28.8°C compared to 1961-1990. This represents a major shift in summer maxima that is also accompanied by a proportional change in the 90% quantile (about 5.5°C) and a similar shift even at the 99<sup>th</sup> percentile level.

The right-hand curves in Figure 4 indicate the cumulative PDFs of maximum temperatures for the 2071-2100 period, and for the 2003 summer heat wave. There is no other instance in the instrumental record in Basel or at many other locations in Switzerland for which summer temperatures fit so closely within the PDF of Tmax in a possible future climate. The mean and median of the 2003 event and the 2071-2100 PDF are very close to one another, but the spread is greater for the 30-year period than for the individual 2003 event, which is to be expected in view of the interannual variability that results in a greater variance over the 30 summers than for a single summer.

Table 1 provides a comparative assessment of climate statistics for Basel observed and simulated for 1961-1990, as well as for future climate in the latter part of the 21<sup>st</sup> century; the table places the 2003 event against the backdrop of current and future climates. The mean and first-order moments of summer Tmax simulated by HIRHAM4 compare well with the observations for current climate, although the model underestimates the average number of days during which a threshold exceedance beyond 30°C is likely to occur. The characteristics of the 2003 heat wave in Europe are seen to bear a far closer resemblance to those of the simulated future climate than to the statistics for 1961-1990 in terms of means, the 90<sup>th</sup> percentile (i.e., the upper extreme of temperature as defined by the IPCC, 2001), threshold exceedance, and the duration of the season during which temperatures may rise above 30°C for a number of separate or consecutive days. For reasons already alluded to, the standard deviation of summer Tmax during the 2003 event are lower than for the 30 years of future climate.

Between 1961-1990 and 2071-2100, the period during which threshold exceedance can be expected is extended by close to one month, beginning on average almost two weeks earlier and ending more than two weeks later than under current climatic conditions. The total number of days during which the 30°C threshold is exceeded increases almost 5-fold in the future, as it did during the 2003 heat wave. The spread of record summer maxima from one year to the next may range from 35-48°C in the future climate, as opposed to a range of 30-38°C for the reference period (38.6°C in 2003).

## Conclusions

The 2003 heat wave, by mimicking quite closely the possible course of summers in the latter part of the 21<sup>st</sup> century, can thus be used within certain limits as an analog to what may occur with more regularity in the future. The physical processes that characterized the 2003 heat wave, such as soil moisture depletion and the positive feedback on summer temperatures, and the lack of convective rainfall in many parts of the continent that generally occur from June-September, are projected to occur with greater frequency in the future. In view of the severity of the impacts related to the persistence of elevated temperatures and drought conditions, such as excess deaths recorded in France and Italy (WHO, 2003), crop failure and sharply reduced animal fodder for the winter in numerous countries (e.g., [www.clivar.org/recent/highlight.htm](http://www.clivar.org/recent/highlight.htm)), and strongly-reduced discharge in many rivers, the recent heat wave as a “shape of things to come” can help both scientists in assessing the course of future climatic impacts, and decision makers in formulating appropriate response strategies.

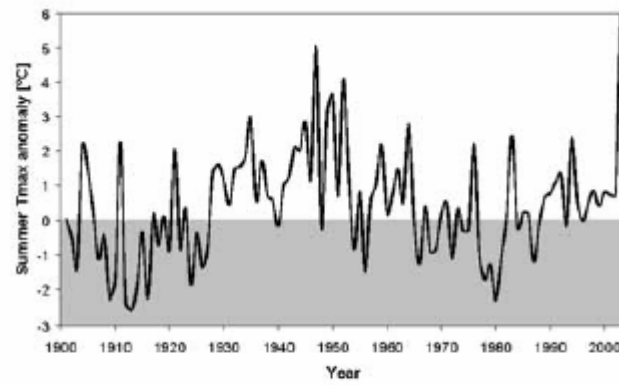
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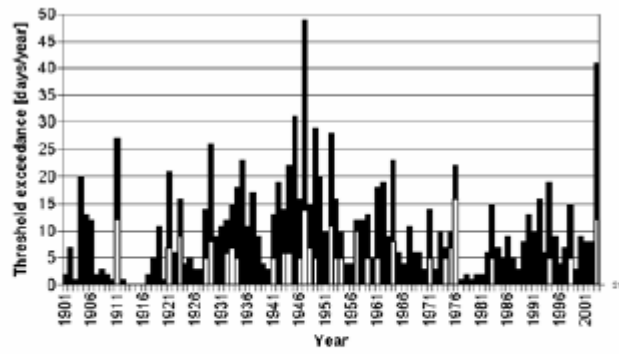
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**Table 1:** Statistics of summer (JJA: June-July-August) daily maximum temperatures observed for the reference period 1961-1990 (in parentheses, simulation of the same period with the HIRHAM4 regional climate model), simulated for future climate 2071-2100 and, in comparison, the 2003 heat wave.

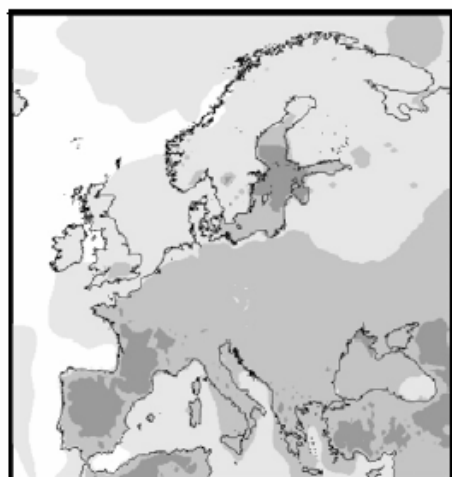
Period	Mean JJA Tmax	90 <sup>th</sup> quantile JJA Tmax	1 $\sigma$ JJA Tmax	Number of days with Tmax > 30°C	Average date with first Tmax > 30°C	Average date with last Tmax > 30°C	Duration of season with Tmax>30°C
1961-1990	23.6°C (23.5°C)	29.6°C (29.1°C)	4.6°C (4.3°C)	8 (7)	June 19 (July 4)	August 19 (August 23)	61 (50)
<b>2003</b>	<b>29.5°C</b>	<b>35.6°C</b>	<b>4.2°C</b>	<b>41</b>	<b>June 2</b>	<b>August 30</b>	<b>89</b>
2071-2100	28.8°C	35.9°C	5.5°C	38	June 7	September 5	90



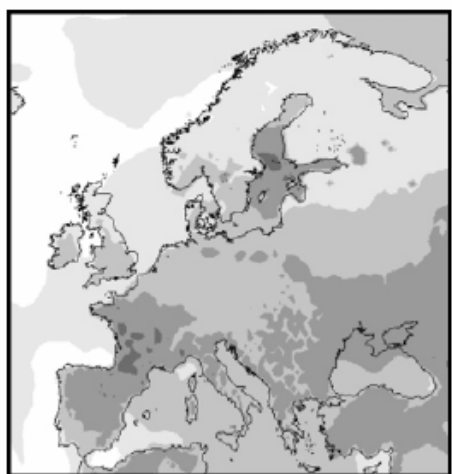
**Figure 1.** Departures of summer maximum temperatures from the 1961–1990 means at Basel (317 m above sea level), Switzerland. Gray shading emphasizes negative anomalies.



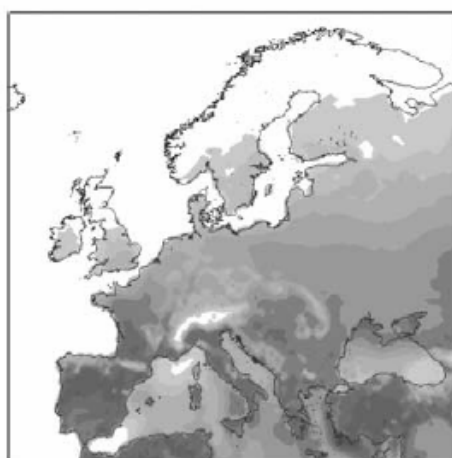
**Figure 2.** Number of days during which temperatures exceed the 30°C threshold in Basel (black) and persistence of threshold exceedance (white), from 1901–2003.



+2 +4 +6 +8 +10 +12°C

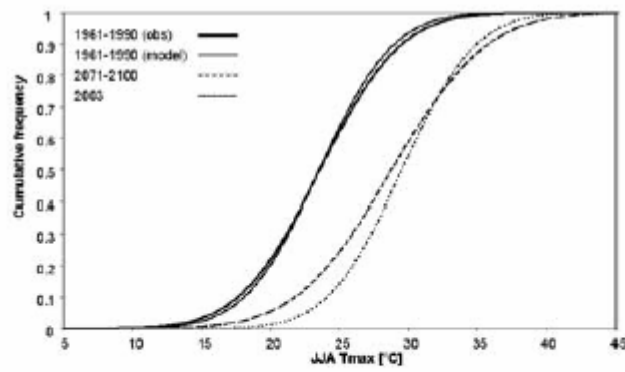


+2 +4 +6 +8 +10 +12°C



1 5 10 20 40 60 80 days

**Figure 3.** Simulations by the HIRHAM4 regional climate model of future summer temperatures in Europe for the time-frame 2071–2100, illustrating changes of mean summer maxima (4a), 90% quantiles of maximum summer temperatures (4b), and the number of days of exceedance of the 30°C threshold (4c), compared to 1961–1990.



**Figure 4.** Cumulative frequency distributions of summer maximum temperatures for the periods 1961–1990 (observed and simulated by the HIRHAM4 regional climate model), 2071–2100, and 2003.