Summer Heat Waves in Western Europe, Their Past Change and Future Projections

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Abstract Summer heat waves and extremely hot temperatures are a serious threat to society, the environment and the economy of Europe. In this chapter we present an overview of selected recent literature which looks specifically at European heat waves and extreme temperature events, their past change and expected future change from 1880 to 2100. Della-Marta et al. (2007b) show that over the period 1880–2005 the length of summer heat waves over western Europe has doubled and the frequency of hot days has almost tripled. These changes are seen in the probability density function (PDF) of western European daily summer maximum temperature (DSMT) as a significant change in the mean (+1.6 ± 0.4°C) and variance (+6 ± 2%). The relatively small change in variance over the last 126 years can explain approximately 40% of the change in hot days. We see a continuation of the observed trends in the future regional projections. Beniston et al. (2007) show that regional surface warming causes the frequency, intensity and duration of heat waves to increase over Europe. By the end of the 21st century, countries in central Europe will experience the same number of hot days as are currently experienced in southern Europe. The intensity of extreme temperatures increases more rapidly than the intensity of more moderate temperatures over the continental interior due to increases in temperature variability.

1 Introduction

Extreme weather and climate events have a large impact on our society and environment (IPCC 2001). Heat waves are especially devastating for societies that are not used to coping with such extremes. The 1995 Chicago heat wave was

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S. Brönnimann et al. (eds.), *Climate Variability and Extremes During the Past 100 Years.*

such an event (Karl and Knight, 1997) where over 500 people died from heat-related illnesses. The 2003 heat wave in Europe is unprecedented in terms of loss of life, with over 30,000 deaths in Europe (Poumadère et al. 2005) attributable to the excessive and persistent heat (Milligan 2004). This extreme event also affected other parts of our society and environment, such as the destruction of large areas of forest by fire, the drying out of rivers causing damage to water ecosystems and the excessive melting of glaciers (e.g., Gruber et al. 2004; Koppe et al. 2004; Schär and Jendritzky 2004; Kovats and Koppe 2005). The sobering results of Stott et al. (2004) show that humans have contributed to at least a doubling of risk of such an extreme event in Europe over the last 150 years. Reducing the impacts of future heat waves requires addressing fundamental questions, such as whether heat waves can be predicted and whether their impacts can be mitigated. A fundamental basis for answering these questions is the analysis of the observed climate record. Comparing observations and model results allow us to test hypotheses on the physical mechanisms that lead to such extreme events (IPCC 2001). Of particular interest in the debate on future extreme temperature events in western Europe is the change in the probability density function (PDF). For example, an increase in both the mean and the variance of a temperature PDF has greater consequences for the duration and frequency of temperature extremes than if the PDF were to only increase in mean. These questions are also explored in two other chapters of this volume, Scherrer et al., who look at changes in the seasonal temperature PDF during the last 45 years compared with projections of future PDF changes, and Seneviratne et al., who detail the underlying physical mechanisms responsible for expected future changes in extreme summer heat events in Europe.

In this chapter we consider a longer-term perspective than the other chapters mentioned above. We present detailed evidence of the increase in the frequency of extremely hot temperatures and an increase in the length of heat wave events in western Europe which have been associated with significant changes in the PDF of the daily maximum temperature from 1880 up to now (Della-Marta et al. 2007b). We also present results of the latest extreme temperature and heat wave regional climate projections for the end of the 21st century (Beniston et al. 2007). Furthermore, this chapter serves as an introduction to the latest literature on the topic of heat waves in Europe. We present results from our collaborations and place them in the context of recent literature. The chapter is separated into three sections. Firstly, we give special emphasis on the data used to assess the changes in summer extreme temperatures in western European over the last 126 years. In the following chapters we show the results of the latest studies concerning observed past and expected future changes in summer hot extreme temperature and heat waves over western Europe. Whilst the extreme temperature indices discussed in these sections are not directly comparable (due to technical differences), they all characterize the extreme hot tail of the daily temperature probability distribution and are aimed at determining the change in frequency and/or persistence of extreme hot temperatures.

2 The Quality of Western European Observed Daily Temperature Data

In order to obtain an accurate estimate of possible climate change all climate data must be rigorously checked for poor quality data and inhomogeneities caused by changes in instruments, observation site, or observation practices. The IPCC Second Assessment Report (Nicholls et al. 1996) raised the awareness of the important consequence of climate change on extreme events and helped to focus greater attention of climate research on this field. Extreme events are often short-lived (minutes to days) and usually require higher temporal and spatial resolution data to quantify their change, compared to quantifying the change in the climatological mean. The analysis of extreme events highlighted the problems with existing data sets and the need to maintain long-term climate stations as part of a consistent high quality network (Karl et al. 1995). In order to detect and attribute changes in the frequency of extreme events it is crucial that, (a) reliable and continuous long-term observations have to be performed with a regular control of the quality standards of the measurements (e.g., by National Weather Services), (b) the quality-controlled data has to be stored for long-term use in a data format which will still be easily accessible in the future. Frich et al. (2002) provided a comprehensive look at changes in extreme temperature events for many parts of the globe for the IPCC Third Assessment Report, which has been updated by Alexander et al. (2006) to cover many more regions of the world, including Africa, the Asia-Pacific region and South America to be included in the IPCC Fourth Assessment Report. A major contribution to the global extremes papers of Frich et al. (2002) and Alexander et al. (2006) in Europe has been the European Climate Assessment (Klein Tank et al. 2002) project which is detailed below as it is the basis of more recent studies which have been made on the analysis of extreme temperature events in Europe (e.g., Della-Marta et al. 2007a, b).

The work of Klein Tank et al. (2002) was the result of extensive collaboration between European national meteorological services which involved the exchange of daily climate data for use in the assessment of climate extremes. The European Climate Assessment data set (Klein Tank et al. 2002) is a collection of many countries' highest quality and longest daily temperature observations. However, in such a large data set, the task of ensuring high data quality and homogeneity has been a huge undertaking for which several strategies have been used. Some of the individual national meteorological services or data providers have performed detailed data quality/homogeneity testing and homogeneity correction their monthly or daily data (e.g., Böhm et al. 2001; Auer et al. 2001; Brunet et al. 2006; Parker and Horton 2005; Begert et al. 2005; Demarée et al. 2002; Moberg et al. 2002; Bergström and Moberg 2002; Herzog and Müller-Westermeier 1998). Other studies have assessed the homogeneity of time series within the data set using the results as a basis for including or excluding particular time series from the data set (Wijngaard et al. 2003; Begert et al. 2007). A further number of studies have improved the quality of the data by screening the data for inconsistencies and outliers (Klein Tank et al. 2002; Moberg et al. 2006; Begert et al. 2007).

These activities have, amongst others, ensured a reliable assessment of changes in extremes over the last 50 years (e.g., Klein Tank and Können 2003). However, in order to assess changes in daily climate extremes over longer periods for which daily data exist there remain considerable challenges in the homogenisation of these data. At the daily timescale there are inhomogeneities in temperature time series which are not adequately accounted for by traditional correction methods (Della-Marta and Wanner 2006). For example, experiments comparing modern instrument shelters with older ones usually show that the earlier shelters allowed the thermometers to be exposed to greater extremes of short- and long-wave radiation (e.g., Parker 1994; Nordli et al. 1997) with nonlinear effects on temperature records throughout the seasonal cycle. In a statistical context, these non-linearities are expressed as a change in the PDF, often with changes in higher-order moments of the PDF. Therefore, there is a need to make adjustments to the entire probability distribution when homogenising daily data (Della-Marta and Wanner 2006). Presently there are only a few methods which have been used to homogenize daily temperature. Current methods either consist of interpolating monthly mean adjustment values to the daily timescale using simple statistical interpolation methods (e.g., Vincent et al. 2002) or more sophisticated methods which can adjust the entire PDF (Trewin and Trevitt 1996; Della-Marta and Wanner 2006). These methods adjust the PDF non-parametrically. Della-Marta et al. (2007a) have applied the method of Della-Marta and Wanner (2006) to 25 long-term daily maximum temperature records contained in the data set described in Moberg et al. (2006). This study is the first to apply a PDF homogenisation method to daily European maximum temperature. Della-Marta et al. (2007a) find that many of the 25 homogenized time series require negative adjustments to the mean and variance of their measured values in order to be homogeneous with current observed values from the same long-term time series. Figure 1 shows an example of a daily adjustment made to the August time series measured at Basel, Switzerland from 1895–1929.

The fitted curve in Fig. 1 shows a negative slope from decile 1 to decile 10. This indicates that the variance of daily maximum temperature in August is too high in comparison with modern measurements (Della-Marta and Wanner 2006). Also notice that the mean adjustment over all deciles is negative. This indicates that the mean daily temperature is also too high in comparison with modern measurements. An analysis by Begert et al. (2005) suggests that the correction needed to August mean temperature in Basel during this period was approximate −0.3°C. The average adjustment in Fig. 1 is −1.6°C showing that the sign of the adjustment is in agreement but the magnitude is much greater using the method of Della-Marta and Wanner (2006). There are many possible reasons for these types of discrepancies which are described in Della-Marta and Wanner (2006), however, the adjustments are intuitively correct since from metadata we know that the thermometer shelter was changed from a more open wall-mounted screen to a free-standing screen. This would result in the need to decrease the variance of daily August maximum temperature to be homogeneous with today's temperatures (see Della-Marta et al. 2007a;

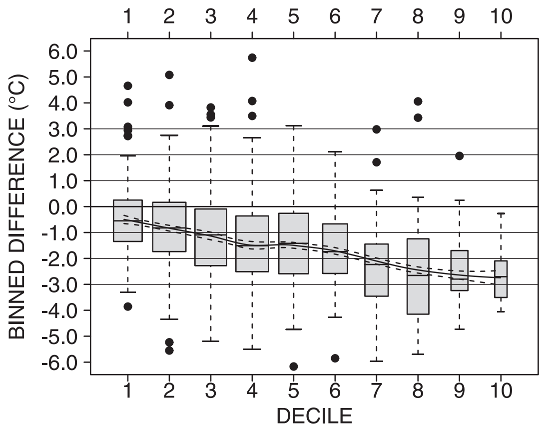

Fig. 1 The adjustment in degree Celsius needed to make August Basel (Switzerland) daily maximum temperature (1895–1929) to be homogeneous with current measurements as a function of the decile of the Basel PDF before the inhomogeneity. The smoothed adjustments (°C) for each percentile shown as a solid black curve fitted using a LOESS function (Cleveland and Devlin 1988). The box plots indicate the mean of the binned differences between modeled and observed daily temperature after the inhomogeneity (black line), the interquartile range (shaded area), 1.5 times the interquartile range (dashed black line), and outliers (dots). The width of the box indicates the relative number of observations in each. The dashed black curved lines show the 95% confidence interval of the fitted curve. See Della-Marta and Wanner (2006) and Della-Marta et al. (2007a) for details of the method and its application respectively

Begert et al. 2005). Della-Marta et al. (2007a) show that many of the 25 stations needed adjustments not only to their mean but also to their variance and skewness characteristics.

The task of homogenising the European Climate Assessment and related European daily data sets (e.g., Moberg et al. 2006) are far from complete, especially for earlier data, however, given a sufficiently dense network of time series (such as the ENSEMBLES daily data set, Begert et al. 2007, http://www.ensembles-eu.org/), automated inhomogeneity detection and correction techniques (e.g., Caussinus and Mestre 2004) may be coupled with daily temperature correction methods (e.g., Della-Marta and Wanner 2006) to provide daily data sets in which the largest and/or most easily detected inhomogenieties known to affect daily temperature data are removed.

3 Heat Wave and Extremely Hot Temperature Changes over the Past 126 Years

In this section we provide an overview of recent studies which have used long-term observational data of daily temperature to document changes in the frequencies of extremely hot temperatures and heat waves over western Europe. All studies agree that mean summer European temperature has increased over the last 126 years. Some studies show that Europe has experienced an unprecedented rate of summer warming in recent decades (Klein Tank and Können 2003; Luterbacher et al. 2004; Klein Tank et al. 2005). The selected studies mentioned below usually used daily temperature data which have different temporal and spatial extent and different levels of data quality. This makes a quantitative intercomparison difficult.

Kyselý (2002) presents a regionally focused paper on the changes in the frequency of heat waves in Prague over the 20th century using homogenized data. The summer daily time series has been shown to be free of urban influences. Using a heat wave index based on fixed thresholds (30°C and 25°C) they conclude that the severity of heat waves in Prague has increased, although they did not fit a trend. At the time of writing the most severe heat wave year was 1994 (during the 1901–1997 period).

Hundecha and Bárdossy (2005) present an analysis of changes in extreme temperatures in the Rhine basin. They conclude that the 90th percentile of summer daily maximum temperature has increased by 1.4°C from 1958–2001. No homogeneity tests were performed since the daily data were assumed to be homogeneous.

Domonkos et al. (2003) document 20th-century trends in extreme warm events in time series from south-central Europe. They use a relatively low fixed threshold of 23°C for all 11 stations and count the number of daily exceedances of this value. They conclude that the frequency of extreme warm events contains large inter-decadal variability with only a few series exhibiting statistically significant trends. They also note that some of the individual trends could be contaminated with inhomogeneities caused by station moves.

Yan et al. (2002) study the trends in summer temperature extremes based on various percentile extremes from eight long-term daily temperature stations. All of the records were homogenized and generally show a decrease in the frequency of extreme warm daily summer temperatures in the 19th and early 20th century followed by an increase in the latter half of the 20th century. However, a more recent study by Moberg et al. (2003) indicates that daily summer temperatures in the Stockholm and Uppsala series (the same used in Yan et al. 2002) may be warm biased before the 1860s due to the thermometers being exposed to higher amounts of short-wave radiation, a finding also supported by Della-Marta et al. (2007a).

Klein Tank and Können (2003) analysed a European climate dataset for changes in the frequency of extreme temperature events. They demonstrated that the annual change in the frequency of hot daily temperature extremes increased twice as fast as corresponding cold daily temperature extremes over the period 1976–1999.

Moberg and Jones (2005) also analysed the same European climate data set but concentrated on analysing the seasonal changes of the sparser but longer time series (some from 1901) in the data set. They found that extremely high summer daily minimum temperature (and to a smaller extent daily maximum temperature) has increased significantly during the past century. There is more evidence for summer warming in the first half of the century compared with the second half. Importantly they note that the European Climate Assessment data set has many daily temperature series whose homogeneity is questionable. They removed those series which had been identified as being the most inhomogeneous by Wijngaard et al. (2003) and they described results which were the most spatially consistent, as they believe they are the most trustworthy.

Moberg et al. (2006) presents an update to Moberg and Jones (2005) by including a greater number of long-term time series starting as early as 1850. These longer time series were collected as part of the EMULATE project (see http://www.cru.uea.ac.uk/cru/projects/emulate/). The authors conclude that regional differences in the magnitude of summer warming can be high and that the strongest increases in the extreme warm summer maximum temperature occurred in central Europe.

Della-Marta et al. (2007b) use a subset of the longest and most complete daily maximum temperature time series from Moberg et al. (2006) (54 time series) to look closer at the summer daily maximum temperature changes over the last 126 years. The time series were homogenized at the daily timescale (Della-Marta et al. 2007a) using the method of Della-Marta and Wanner (2006). The homogeneity analysis shows that many summer daily maximum temperature series in western Europe are biased warm in the earlier parts of their time series (Della-Marta et al. 2007a) believed to be caused mainly by early thermometers being exposed in open type, metallic or wall-mounted radiation shields. Compared to modern radiation shields (e.g., the Stevenson screen) the older types generally allowed the thermometers to be exposed to more short- and long-wave radiation.

Della-Marta et al. (2007b) placed the observations of increased daily summer maximum temperature (DSMT) variance in recent years (Klein Tank et al. 2005; Moberg et al. 2006) into a longer-term perspective. They show that the recently observed increase in summer daily and summer seasonal (~45 years, see Scherrer et al., this volume) temperature variability in western Europe is indeed unique over the last 126 years. Over western Europe the variance of DSMT across western Europe has increased significantly by approximately 6 ± 2% and by 11 ± 2% for central-western Europe (see Table 1 and Della-Marta et al. 2007b).

These changes can be seen in the PDF of western European DSMT which has become flatter and wider (see Fig. 4a in Della-Marta et al. 2007b). In order to accurately

Table 1 Daily Summer Maximum Temperature mean, variance and skewness trends from 1880 to 2005, for each of four regions in western Europe. (Reproduced from Della-Marta et al. 2007b.)

Region (Number of stations)	Mean (°*C*)	Variance (%)	Skewness (%)
Western Europe (54)	**1.6 ± 0.4**	**+6 ± 2**	+0 ± 7
Central Western Europe (36)	**1.3 ± 0.5**	**+11 ± 2**	+0 ± 6
Iberian Peninsula (12)	**2.6 ± 0.6**	**−7 ± 3**	−1 ± 12
Scandinavia (6)	**1.7 ± 0.7**	+4 ± 6	**+9 ± 6**

Trends have been calculated over nine independent periods. The mean, variance and skewness trends are expressed in the units of °C, % and % with respect to 1906–1990 period respectively. The error estimates are 95% confidence intervals based on the standard error of the robust linear fit. Figures quoted in bold face are significantly (5% significance) different from zero. (See Della-Marta et al. (2007b) for more details.)

assess the change in DSMT variance, data are split into independent periods of 14 years and have had the linear trend removed using a technique called piece-wise detrending (Scherrer et al., this volume; Scherrer et al. 2005; Della-Marta et al. 2007b). Della-Marta et al. (2007b) show that western European DSMT has increased by 1.6 ± 0.4°C from 1880 to 2005 consistent with all previous studies, however, they find that as a result of the homogenisation applied to the daily data (Della-Marta et al. 2007a) the estimate of climate change in western Europe is more extreme than any published before. Figure 2 is reproduced from Della-Marta et al. (2007b) and shows the temporal and spatial distribution of changes in hot days (HD) and maximum length heat wave (HW) over the last 126 years. A HD is defined as a day where the daily maximum temperature exceeds the long-term daily 95th percentile of daily maximum temperature. The hot day index (HD) is the number of such days within a June–August season expressed as a percentage of time. A heat wave (HW) is defined as the maximum number of consecutive days where the DSMT exceeds the long-term daily 95th percentile of DSMT within a June–August season. The daily 95th percentile is calculated using a centred 15-day average using the daily data from the normal period of 1906–1990. They find that

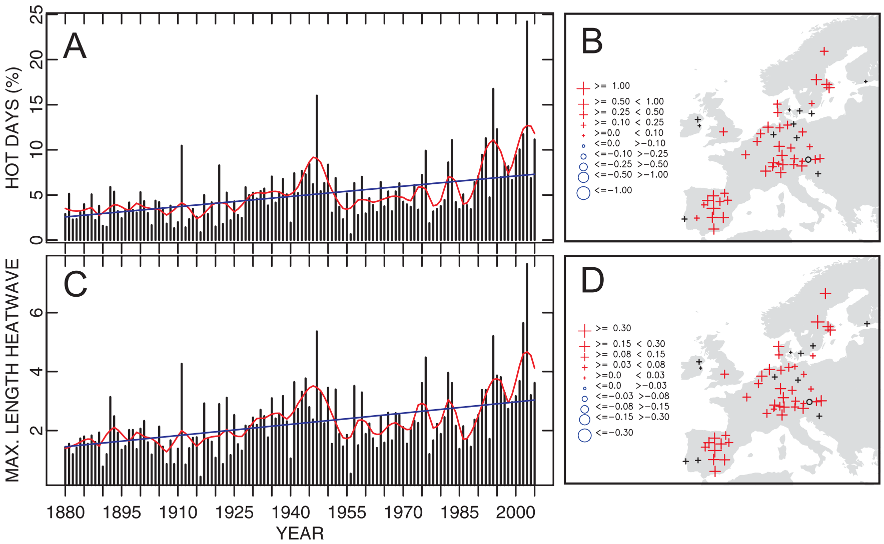

Fig. 2 Reproduced from Della-Marta et al. (2007b): June–August average number of western European hot days (HD) (a) and maximum length heat wave (HW) (c) from 1880 to 2005. The long-term decadal variability (thick red line) and the overall robust linear trend (thick blue line) are shown. The units of HDs are percent of June–August days and the units of HWs are days. The spatial distribution of decadal HD (b) and HW d) trends at each station. The size of the "+" and "o" symbols is proportional to the magnitude of the positive and negative trends respectively according to the legend left of the figure. Red (black) coloured crosses indicate significant (not significant) positive trends at the 5% significance level (Similarly for negative trends). (See Della-Marta et al. (2007b) for more details)

almost all station records used in their analysis have a positive trend in the occurrence of summer HDs and HWs from 1880 to 2005 (Fig. 2b, d). Around 80% of the trends are significant (Della-Marta et al. 2007b). The largest trends have been found over the Iberian Peninsula and in central-western Europe. The time evolution of European average HDs (Fig. 2a) shows an overall positive trend of 0.38 ± 0.05% of summer days per decade. This trend is equivalent to approximately 188 ± 54% increase, with an average of 7.3% of summer days classified as HDs at the end of the period, compared with 2.5% in 1880. The 6 ± 2% and the 11 ± 2% increase in DSMT variance over the whole of western Europe and central-western Europe is responsible for approximately 25% and 40% of the increase in HDs in these regions respectively. This confirms that small changes in the intrinsic variance of DSMT have lead to greatly amplified changes in the frequency of extremes. Similarly, the length of HWs has increased by approximately 111 ± 36%, from an average of 1.4–3.0 days per HW (Fig. 2c). As a result, HWs have doubled in length over the period 1880–2005. The changes in the HW index are especially important since this index combines a measure of the extreme temperature magnitude as well as a measure of their persistence (Della-Marta et al. 2007b).

4 Projections of Heat Wave and Extremely Hot Temperatures

In this section we outline some of the recent literature concerning future changes in the frequency of extremely hot temperatures and heat waves in Europe. Some studies are based on the output of general circulation models (GCM) forced by expected changes in greenhouse gases, aerosols and other known forcings. Other studies nest regional climate models (RCM) within GCMs to try and get more realistic estimates of temperature change at higher resolutions. Projections of temperature in Europe all agree that mean temperature and the frequency of extremes will increase during the next 100 years (Wagner 1996; Huth et al. 2000; Beniston 2004; Meehl and Tebaldi 2004; Schär et al. 2004; Weisheimer and Palmer 2005; Clark et al. 2006; Beniston et al. 2007); however, the precise magnitude of this change is uncertain due to uncertainties in the estimates of global greenhouse gas emissions and biases in GCMs/RCMs due to inadequate parameterisations of unresolved physical processes. Many of the simulations performed by RCMs are based either on the IPCC SRES A2 high greenhouse gas emissions scenarios or the lower B2 scenario (Nakicenovic et al. 2000), that both have a large number of underlying assumptions on the future course of global population, economics, technological adjustments and political decision-making. In the following, the A2 scenario results are highlighted as they represent the upper range of greenhouse gas forcing and thus potentially lead to some of the strongest impacts.

RCM projections of summer extreme temperature change in Europe suggest that there will be substantial regional variation linked with complex feedback mechanisms between soil moisture, precipitation and circulation (Schär et al. 2004; Brabson et al. 2005; Ferranti and Viterbo 2006; Seneviratne et al., this volume; Seneviratne et al.

2006; Beniston et al. 2007). Decreased levels of soil moisture in central and eastern future European climate have been shown to be responsible for the projected increases in summer temperature variability (Schär et al. 2004; Seneviratne et al., this volume; Seneviratne et al. 2006), a trend which is seen in many other projections of European climate change (Scherrer et al., this volume; Scherrer et al. 2005; Weisheimer and Palmer 2005; Beniston et al. 2007) and in some cases is expected to be as large as 100% in 2071 compared to the climate of 1961–1990 (Schär et al. 2004).

Beniston et al. (2007) present a summary of future projections of European extreme events (including heat waves) which have been shown to have a high impact on European society and the environment. They summarize the findings of 55, 30-year integrations from a variety of RCMs created as part of the PRUDENCE project (http://prudence.dmi.dk/index.html). The experiments compare present control climate simulations over the period 1961–1990 with 2071–2100 simulations. Beniston et al. (2007) use a number of indices to investigate changes in extreme temperatures and heat waves: the frequency with which daily maximum temperature exceeds 30°C, high temperature percentiles, and four heat wave indices. A heat wave is defined to be a spell of at least six consecutive days with maximum temperature exceeding the 1961–90 calendar day 90th percentile, calculated for each day over a centred 5-day window at each grid point. The four indices, calculated for each year are: Heat Wave Number (HWN); the number of heat waves, Heat Wave Frequency (HWF); the total length (days) of all heat waves, Heat Wave Duration (HWD); the maximum length (days) of all heat waves (very similar to the definition of HW), and, Heat Wave Intensity (HWI); the maximum threshold excess (degree days) of all heat waves.

High percentiles of daily maximum temperature across Europe generally increase more than lower percentiles, implying that changes in the PDFs are more than shifts in location. Changes in the variance (as well as the mean) of daily maximum temperatures have a substantial impact on future extreme daily temperatures. Largest changes in variance were found over the continental interior (a latitude band encompassing France and Hungary; see also Schär et al. 2004) and are most likely caused by a drying out of the land surface in warmer and drier future summer conditions.

Figure 3 shows the changes in the four heat wave indices simulated by HIRHAM-H, expressed as ratios. The mean duration (HWD, Fig. 3a) increases by a factor of between one and eight over most of Europe. Much higher increases of at least a factor of seven are predicted for the mean intensity (HWI, Fig. 3b), the mean number of heat waves (HWN, Fig. 3c) and the frequency of heat wave days (HWF, Fig. 3d), with greatest changes (more than tenfold increases) in the south of France and Spain.

Figure 4 shows the shift in JJA maximum temperature between the 1961–1990 reference period and 2071–2100 for the RCM grid-point closest to Basel (northwestern Switzerland), for the IPCC A2 and B2 scenarios, for both the mean and the 90% quantile. In the reference climate, mean temperatures in Basel are close to 23°C and heat waves can be considered to occur when temperatures exceed 30°C (which is the average level of the 90% quantile for this period). For the scenario

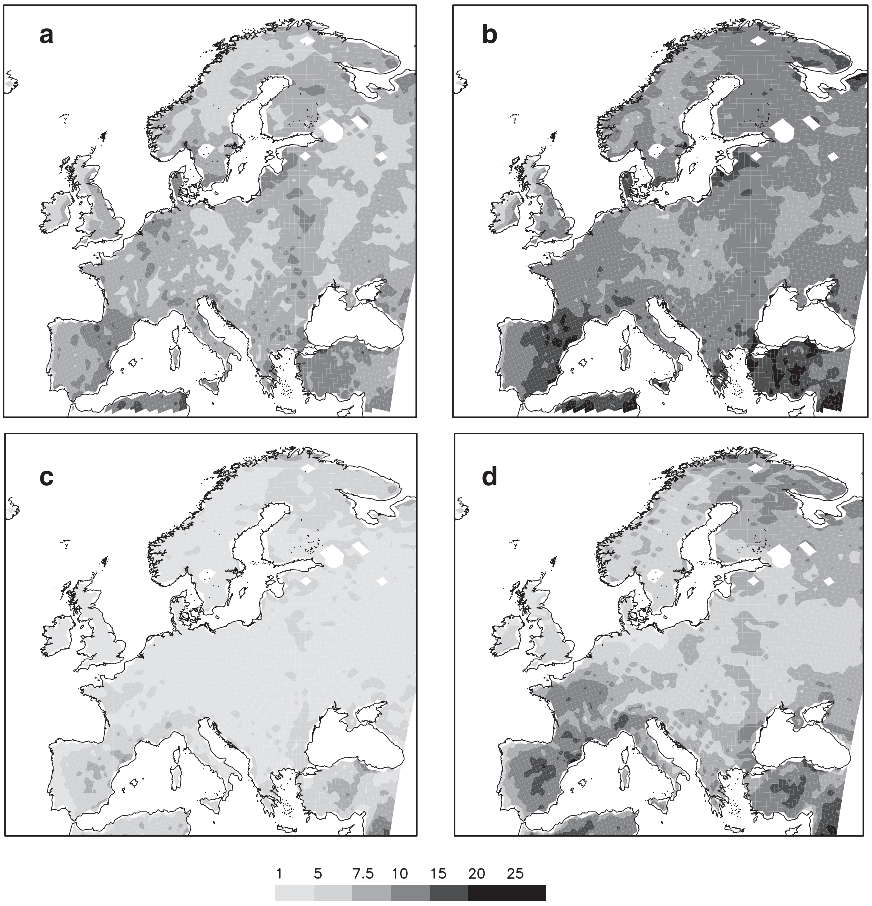

Fig. 3 Changes (expressed as a ratio) in the heat wave indices (a) HWN (b) HWF (c) HWD d) HWI indices between the 1961–1990 and 2071–2100 periods, based on HIRHAM4 simulations. A heat-wave is defined to be a spell of at least six consecutive days with maximum temperature exceeding the 1961–1990 calendar day 90th percentile, calculated for each day over a centred 5-day window at each grid point. The four indices, calculated for each year, are Heat Wave Number (HWN) – the number of heat waves, Heat Wave Frequency (HWF) – the total length (days) of all heat waves, Heat Wave Duration (HWD) – the maximum length (days) of all heat waves, Heat Wave Intensity (HWI) – the maximum threshold excess (degree days) of all heat waves (see Beniston et al. 2007 for more details). (Reproduced from Beniston et al. 2007)

climates, whatever the scenario chosen, temperatures are seen to rise on average between 5°C and 7°C over current values; the difference in temperature between the A2 and B2 emissions scenarios is less than between the low emissions scenario and current climate. This implies that even with rather stringent policies to abate greenhouse gas emissions, the increase in temperatures as seen for the B2 scenario may ultimately result in summer heat waves that are as intense, or even stronger,

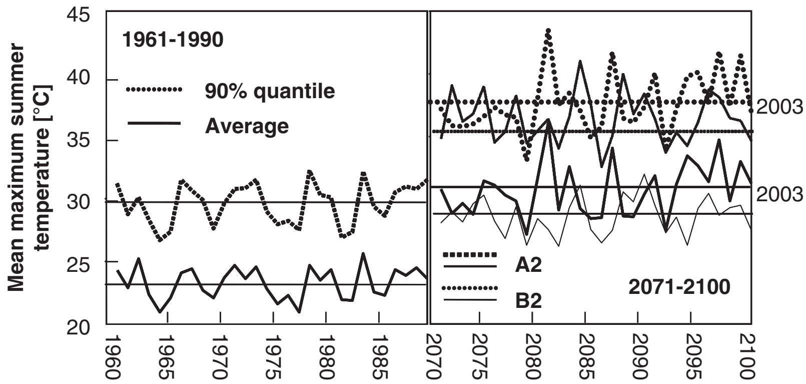

Fig. 4 Comparisons between summer (JJA) mean maximum temperatures and their 90% quantiles for Basel, for each year of the reference 1961–1990 climate and the A2 and B2 scenario climates. The horizontal lines depict the 30-year means for each time series. 2003 refers to the mean and 90% quantile values recorded during the summer of 2003 in Europe, in order to highlight the exceptional nature of that heat wave. (Reproduced from Beniston and Diaz 2004)

than the 2003 European heat wave; the potential for strong heat waves is even greater for the A2 scenario, as can be intuitively expected when greenhouse forcing is stronger. The mean and 90% quantile statistics of the 2003 heat wave are provided in this diagram to highlight the fact that this event was exceptional and could be considered to be a "summer of the future". Indeed, statistically speaking, the 2003 heat wave could occur one summer out of two in a future climate (Schär et al. 2004).

The 2003 heat wave, by mimicking quite closely the possible course of summers in the latter part of the 21st century, can thus be used within certain limits as an analogue to what may occur with more regularity in the future. The physical processes that characterised the event, such as soil moisture depletion and the positive feedback on summer temperatures as well as the lack of convective rainfall in many parts of the continent that generally occur from June–September, are predicted to take place with greater frequency in the future. In view of the severity of the impacts related to the heat wave, it should help scientists in assessing the course of future climatic impacts, and decision-makers in formulating appropriate response strategies. It is of interest to note, however, that according to the baseline used, the very definition of a heat wave could change in a future, systematically warmer climate. The climate of southern Spain, for example, that is currently characterized by temperatures exceeding 30°C for about 60 days per year on average may in the future experience over 150 days or more (Beniston and Diaz 2004). Under such circumstances, the notion of heat wave loses some of its value when a rare or exceptional feature of today's climate becomes commonplace in tomorrow's climate. This aspect of changing extreme events in a warmer world also needs to be taken into account in forward planning to adapt to the impacts of such events.

5 Conclusions

We presented a brief overview of the latest literature concerning observed and future estimates of the change in the frequency of extreme temperature events and the duration of heat waves in Europe spanning the period between 1880 and 2100. We have given special attention to summarising the current efforts to improve the quality of observed daily temperature series in Europe. A new method (Della-Marta and Wanner 2006) has been used to correct previously uncorrected inhomgeneities in some early European daily temperature measurements (Della-Marta et al. 2007a). We focused the presentation of results from two recent publications on observed changes in heat waves from 1880 to 2005 (Della-Marta et al. 2007b) and future expected changes of heat waves (Beniston et al. 2007). Below we combine and summarize the important findings from the literature.

- New analyses reveal that the increases in western European extreme temperatures from 1880 to 2005 is greater than previously thought (Della-Marta et al. 2007b).
- Observations of regional changes in mean and variance of daily summer maximum temperature (Della-Marta et al. 2007b) fall in line with expected future summer temperatures in Central- western Europe (Schär et al. 2004; Seneviratne et al. 2006; Beniston et al. 2007). This region, where the largest observed increase in daily summer maximum temperature of 11 ± 2% (see Table 1) from 1880 onwards occurred, is also the region with the greatest expected change in summer temperature variability, with changes up to 100% by 2071–2100 (Schär et al. 2004).
- The expected large increase in temperature variability in Central- western Europe is likely to be driven in part by soil moisture, precipitation and atmospheric circulation feedback processes (Schär et al. 2004; Seneviratne et al. 2006; Beniston et al. 2007).
- Approximately 40% of the change in the frequency of hot days over the last 126 years in central-western Europe is due to increases in the daily summer maximum temperature variance. In the future climate up to 60% of change in the frequency of hot days could be due to changes in summer daily temperature variability.
- The duration of heat waves (based on the daily 95th percentile) in each summer season since 1880 have doubled in length (Della-Marta et al. 2007b). The projected future increase in the duration of slightly less extreme heat waves (based on the daily 90th percentile) is estimated to be between a factor of 1 and 8 by 2100 (Beniston et al. 2007).

Acknowledgement This study was supported by the Swiss NSF through the National Centre for Competence in Research Climate (NCCR-Climate).

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