Critical Reviews in Environmental Science and Technology, 40:267–306, 2010

ISSN: 1064-3389 print / 1547-6537 online
DOI: 10.1080/10643380802238137

A Review of the European Summer Heat Wave of 2003

R. GARCÍA-HERRERA,[1] J. DÍAZ,[2] R. M. TRIGO,[3,4]
J. LUTERBACHER,[5] and E. M. FISCHER[6,7]
[1]*Departamento Física de la Tierra II, Facultad de CC Físicas, Universidad Complutense de Madrid, Ciudad Universitaria, 28040 Madrid, Spain*
[2]*Escuela Nacional de Sanidad, Instituto de Salud Carlos III, Madrid, Spain*
[3]*CGUL, IDL, Faculdade de Ciências, Universidade de Lisboa, Portugal*
[4]*Departamento de Engenharias, Universidade Lusófona, Lisbon, Portugal*
[5]*Justus-Liebig University of Giessen, Giessen, Germany*
[6]*Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland*
[7]*National Center for Atmospheric Research, Boulder, Colorado, USA*

This paper reviews the European summer heat wave of 2003, with special emphasis on the first half of August 2003, jointly with its significant societal and environmental impact across Western and Central Europe. We show the pattern of record-breaking temperature anomalies, discuss it in the context of the past, and address the role of the main contributing factors responsible for the occurrence and persistence of this event: blocking episodes, soil moisture deficit, and sea surface temperatures. We show that the anticyclonic pattern corresponds more to an anomalous northern displacement of the North Atlantic subtropical high than a canonical blocking structure, and that soil moisture deficit was a key factor to reach unprecedented temperature anomalies. There are indications that the anomalous Mediterranean Sea surface temperatures (SSTs) have contributed to the heat wave of 2003, whereas the role of SST anomalies in other oceanic regions is still under debate. There are methodological limitations to evaluate excess mortality due to excessive temperatures; however, the different studies available in the literature allow us to estimate that around 40,000 deaths were registered in Europe during the heat wave, mostly

Address correspondence to R. García-Herrera, Departamento Física de la Tierra II, Facultad de CC Físicas, Universidad Complutense de Madrid, Ciudad Universitaria 28040 Madrid, Spain; E-mail: rgarciah@fis.ucm.es

elderly persons. Despite previous efforts undertaken by a few cities to implement warning systems, this dramatic episode has highlighted the widespread un-preparedness of most civil and health authorities to cope with such large events. Therefore, the implementation of early warning systems in most European cities to mitigate the impact of extreme heat is the main consequence to diminish the impact of future similar events. In addition to mortality (by far the most dramatic impact), we have also analyzed the record-breaking forest fires in Portugal and the evidence of other relevant impacts, including agriculture and air pollution.

KEY WORDS: heat waves, extreme events, climate impacts

INTRODUCTION

According to the State of Climate in 2003 report (Levinson & Waple, 2004), the global annual mean surface temperature in 2003 was among the three highest observed during the period of regular instrumental records. In 2003, global surface temperatures are estimated to be 0.46°C above the 1961–1990 mean. In Europe, annual land surfaces temperature anomalies within the area 45°–65°N and 25°W–60°E were 0.66°C above the 1961–1990 average. There were significant regional and seasonal variations; temperatures across the Mediterranean, southern Adriatic, and much of the northwestern part of the European continent were above the 98th percentile of the 1961–1990 distribution averaged over the entire year. In general, 2003 was also very dry, especially during February, March, and most of the summer season, despite some regional flooding events in the Danube and Elbe catchments (Levinson & Waple, 2004). Figure 1 shows the spatial surface air temperature anomaly (with respect to the 1961–1990 reference period) pattern of the summer (June–August) 2003 (data from GISTEMP, http://data.giss.nasa.gov/gistemp/maps/) (Hansen et al., 2001). The largest departures are found over the U.S. west coast and continental Europe. Globally, the 2003 summer temperatures were 0.41°C higher than the 1961–1990 average.

At European scale (see the black box in Figure 1), the temperatures exceeded +1.9°C (around two standard deviations); in the center of the anomaly (Switzerland), the summer average was 4° to 5.5°C higher than the 1961–1990 reference period, a value higher than three standard deviations. Two distinct periods of exceptional heat occurred during the season: the first in June and the second during the first half of August (Schär & Jendritzky, 2004; Schär et al., 2004). During the August heat wave episode, hereafter referred to as European Heat Wave 2003 (EHW03), temperatures reached considerably larger anomalies than in June at both the daily and weekly

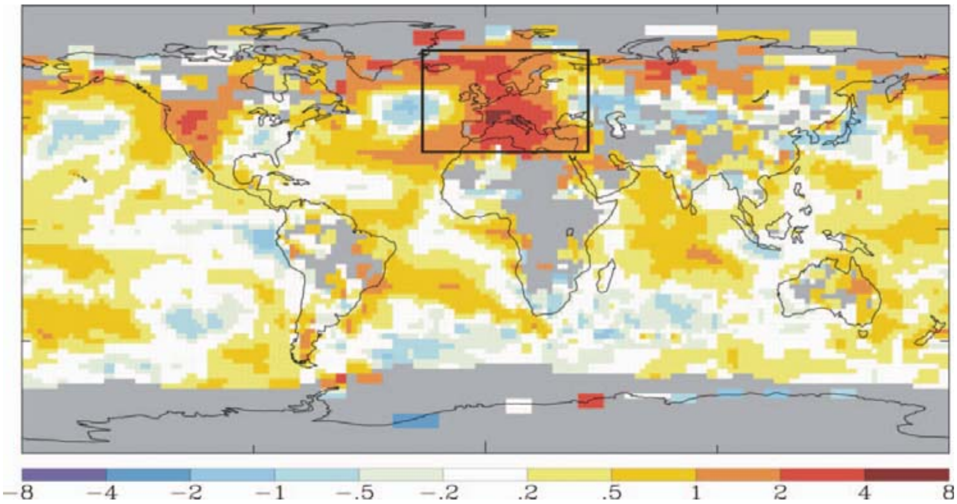

FIGURE 1. Surface air temperature anomalies (in °C, with respect to the 1961 to 1990 reference period), June–August 2003. Data source: Hansen et al., 2001; NASA/GISS (http://www.giss.nasa.gov/cgi-bin/update/gistemp/).

scale. Different analysis of data performed by several European meteorological services showed that France, Germany, Switzerland, Portugal, and the UK experienced record-breaking maximum temperatures during EHW03 (Beniston, 2004; Burt, 2004; Fink et al., 2004; Levinson & Waple, 2004; Schär et al., 2004; Schönwiese et al., 2004; Trigo et al., 2006). Daily maximum temperatures during this period exceeded 40°C across most of interior Spain and central Portugal, 36°–38°C across southern and central France, and 32°–36°C across northern France. In general, these temperatures were 7.5°–12.5°C above average. For the areal average of Germany, both June and August were the warmest months since the beginning of the twentieth century (e.g., Schönwiese et al., 2004). Thus, the summer (JJA) became the hottest in Germany since 1901 (average temperature of 19.6°C, which was 3.4°C above the 1961–1990 base period), and, with the exception of some stations in northern and northwestern Germany, it was the hottest summer since the beginning of recorded measurements (Levinson & Waple, 2004). Also, in Portugal, the historical record of absolute extreme temperatures was surpassed on the 1st of August, with the maximum (minimum) temperature reaching a new all-time record of 47.3° (30.6°) near the border with Spain (Trigo et al., 2006). However, perhaps the most relevant feature of the EHW03 was the lack of cool temperatures and the large number of very warm days (Rebetez, 2004), even in countries such as Spain, where no historical records were exceeded.

Very few extreme episodes have received as much attention as the EHW03 due to a number of reasons (see Alcamo et al., 2007, for a review in the IPCC 4th Assessment Report). This extreme episode was directly associated with approximately 40,000 extra deaths, particularly those of elderly Europeans. It corresponds to 20 times the excess mortality recorded during the 1995 Chicago heat wave. Perhaps the only recorded precedent in terms of mortality can be identified in 1743 in Beijing, when 11,000 deaths were reported associated to excessive temperatures (see Bouchama, 2004, and references therein). Heavy losses in crops, a loss of 10% of mass in Alpine glaciers, temperature records in lake waters, and an unprecedented shortage of the pollen season, jointly with threats to water and energy supply systems, were also recorded (e.g., Gehrig, 2006; Gruber et al., 2004; Haeberli et al., 2005). Additionally, the EHW03 demonstrated the failure of social and health systems to react adequately to this type of extreme events, which may become more frequent in the future, according to climate change scenarios obtained with the state-of-the-art climate models (Beniston, 2004; Beniston & Díaz, 2004; Meehl & Tebaldi, 2004; Schär et al., 2004; Stott et al., 2004). A deep understanding of the impacts and their causes will help to implement future adaptation strategies that were absent during EHW03.

This paper reviews the main features associated to the EHW03 from a multiple perspective. First, we analyze the meteorological patterns and contributing factors that led to the EHW03 occurrence; the following section analyzes the EHW03 from a paleoclimatological perspective. Then we review the most relevant impacts, in the society and the ecosystems, described in the literature, while the final section summarizes the main lessons that can be drawn from this event.

CHARACTERISTICS OF THE 2003 EUROPEAN SUMMER HEAT WAVE

Several authors (e.g. Black et al., 2004; Carril et al., 2008; Della-Marta et al., 2007a, 2007b; Ferranti et al., 2006; Fischer et al., 2007a, 2007b; Schär et al., 2004) have stressed that the outstanding temperatures reached during the EHW03 could not have happened without important anomalous conditions (e.g., SST and soil moisture) during the previous seasons (i.e., the winter and spring of 2003). In order to analyze these anomalies, we have retrieved data from 2003 from NCEP-NCAR reanalyses (Kistler et al., 2001) for 500 hPa geopotential height and 850 hPa temperature as well as sea level pressure (SLP). Monthly anomalies (with respect to the 1961–1990 reference period) between January 2003 and August 2003 have been calculated for fields of 500 hPa geopotential height (see Figure 2) and SLP (see Figure 3) covering the area of Europe. Grey shading highlights those regions where these anomalies (SLP and 500 hPa geopotential height) are significantly different from the average climatology (5% and 10% significance level, based on a students t test). We have used the monthly precipitation dataset at 1.0° by 1.0°

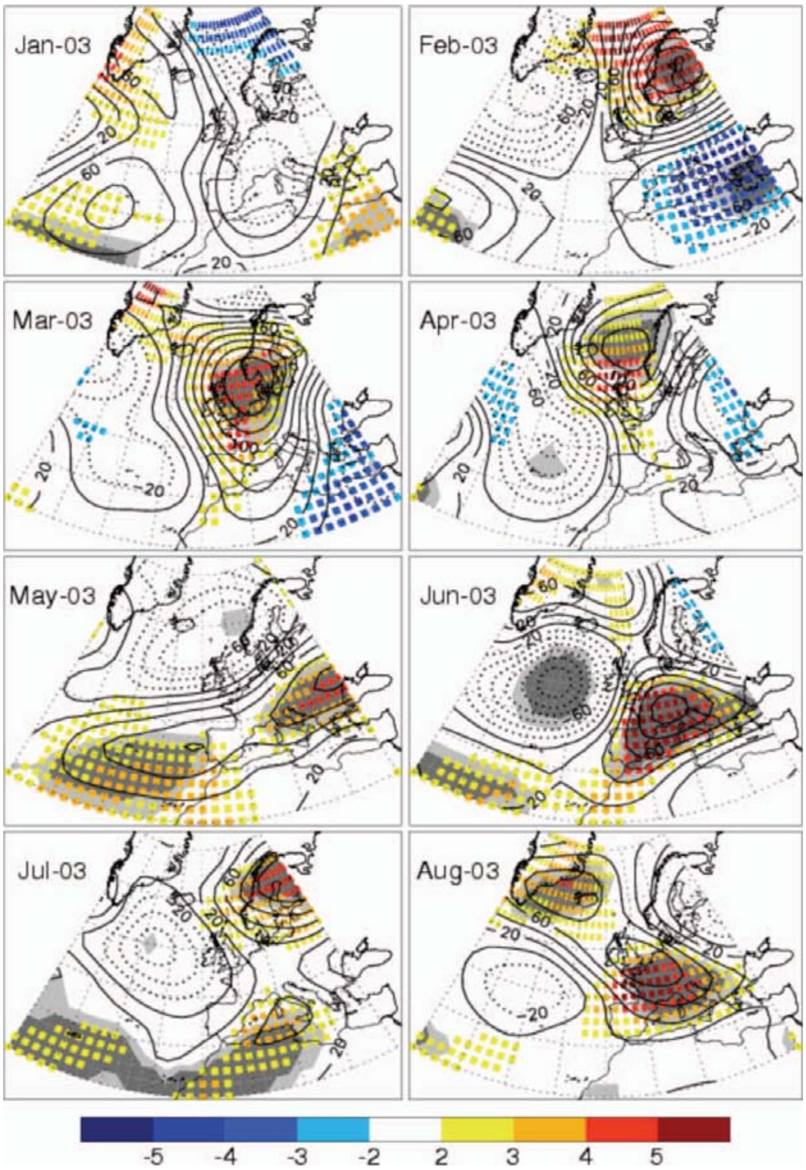

FIGURE 2. Monthly anomalies of 500 hPa geopotential height (gpm) between January and August 2003 with respect to the period 1961–1990. The shading highlights those regions where these anomalies are significantly different from the climatology at the 10% and 5%. The colored squares represent the corresponding 850 hPa temperature anomaly field (°C). All data from NCAR/NCEP reanalyses.

resolution from the GPCC (freely available at http://gpcc.dwd.de; see Rudolf et al., 2007) to calculate the monthly anomalies (see Figure 3). The anomalous conditions between February and April had several major consequences:

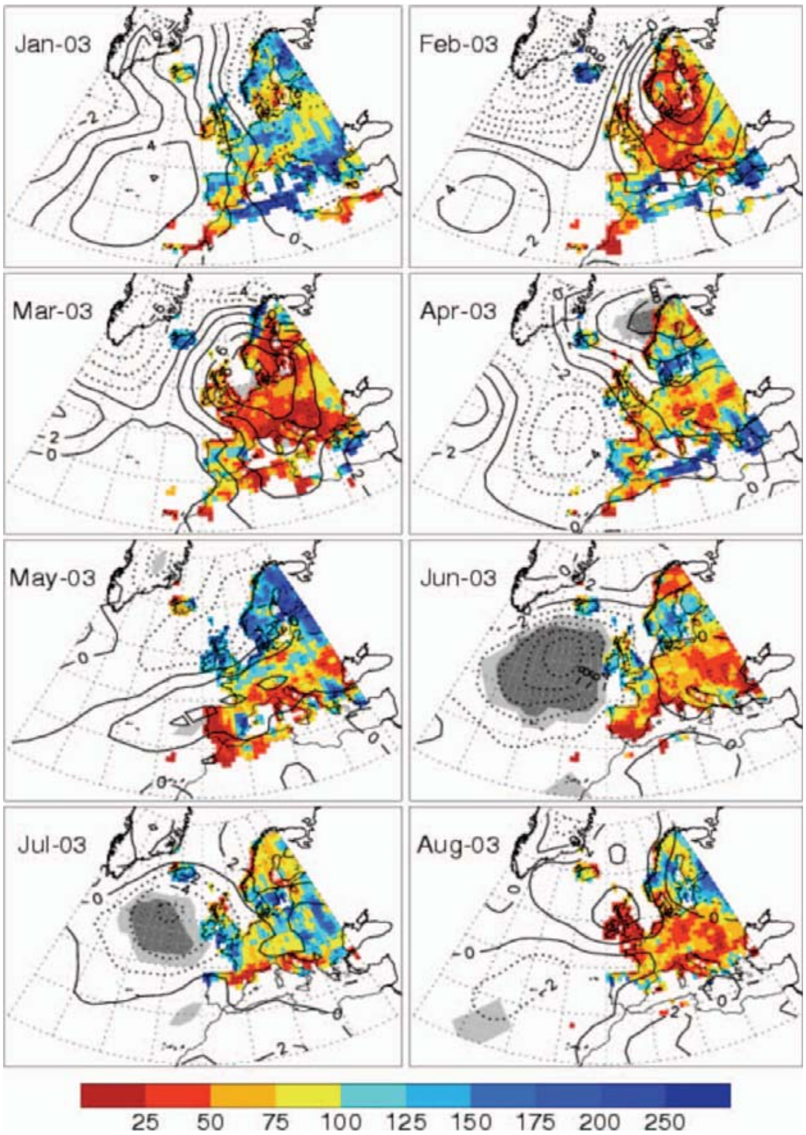

FIGURE 3. Monthly anomalies of SLP (hPa) between January and August 2003. The shading highlights those regions where these anomalies are significantly different from the climatology at the 10% and 5% level (data from NCAR/NCEP reanalyses). The colored shading represents the corresponding precipitation percentage from the normal 1961–1990 (data from GPCC, freely available at the GPCC site: http://gpcc.dwd.de).

- There were large positive temperature anomalies in the lower troposphere and at the surface extending between the British Isles and Scandinavia (see Figure 2);
- There were also large and persistent negative precipitation anomalies between Scandinavia and the central Mediterranean (see Figure 3).

Meanwhile, western (Iberia) and eastern (Turkey) sections of the Mediterranean basin experienced higher than average precipitation.

- Another important consequence of the intense NW-SE gradient of SLP and mid-tropospheric geopotential height levels, for the February–April 2003 period, was the strong advection of cooler air from northern latitudes toward the eastern Mediterranean. This is particularly clear for February 2003, displaying 850 hPa temperature anomalies lower than –2°C all over Western Europe (see Figure 2).

Figure 4 shows bi-daily values of T_{850} anomalies for the period 1–14 August 2003. Daily T_{850} anomalies were computed as departures from the corresponding daily climatology (NCEP reanalysis, 1958–2002), computed as in a previously developed procedure (Trigo et al., 2005, 2006) to show the area where previous absolute maximum values were exceeded in the European sector. If the value for a particular region falls above the daily climatological maximum, then the exceeding temperature difference above that 45-year absolute maximum is also plotted (solid lines). It can be seen that the previous absolute maximum is exceeded for the first time over southern Portugal on the 1st of August, when the anomalies achieved values higher than 9°C. Again, on August 2nd, the central sector of Portugal and western Spain recorded new extreme values, with anomalies of up to 11°C (not shown). The anomaly migrated northeast on August 3, presenting a core sector (>11°C) that stretches from northwestern Spain to western France. Interestingly, this anomaly does not exceed previous maxima since 1958. The daily patterns between August 5 and 13 showed record-breaking anomalies over northern France and southern England (daily anomalies higher than 13°C). The first day with no historical record surpassed was the 14th of August.

THE EUROPEAN SUMMER OF 2003 IN THE CONTEXT OF THE LAST CENTURIES

Luterbacher et al. (2004) published monthly and seasonal European temperature reconstructions back to 1500 using a combination of long instrumental data, documentary proxy evidence, and a few seasonally resolved natural proxies. As in Xoplaki et al. (2005), the reconstructions of Luterbacher et al., (2004) were recalculated fitting to the new updated gridded Mitchell and Jones (2005) data by using only long instrumental temperature data and temperature indices derived from documentary evidence (Luterbacher et al., 2007). The updated summer mean series from 1500–2006 is presented in Figure 5 (Xoplaki et al., 2006).

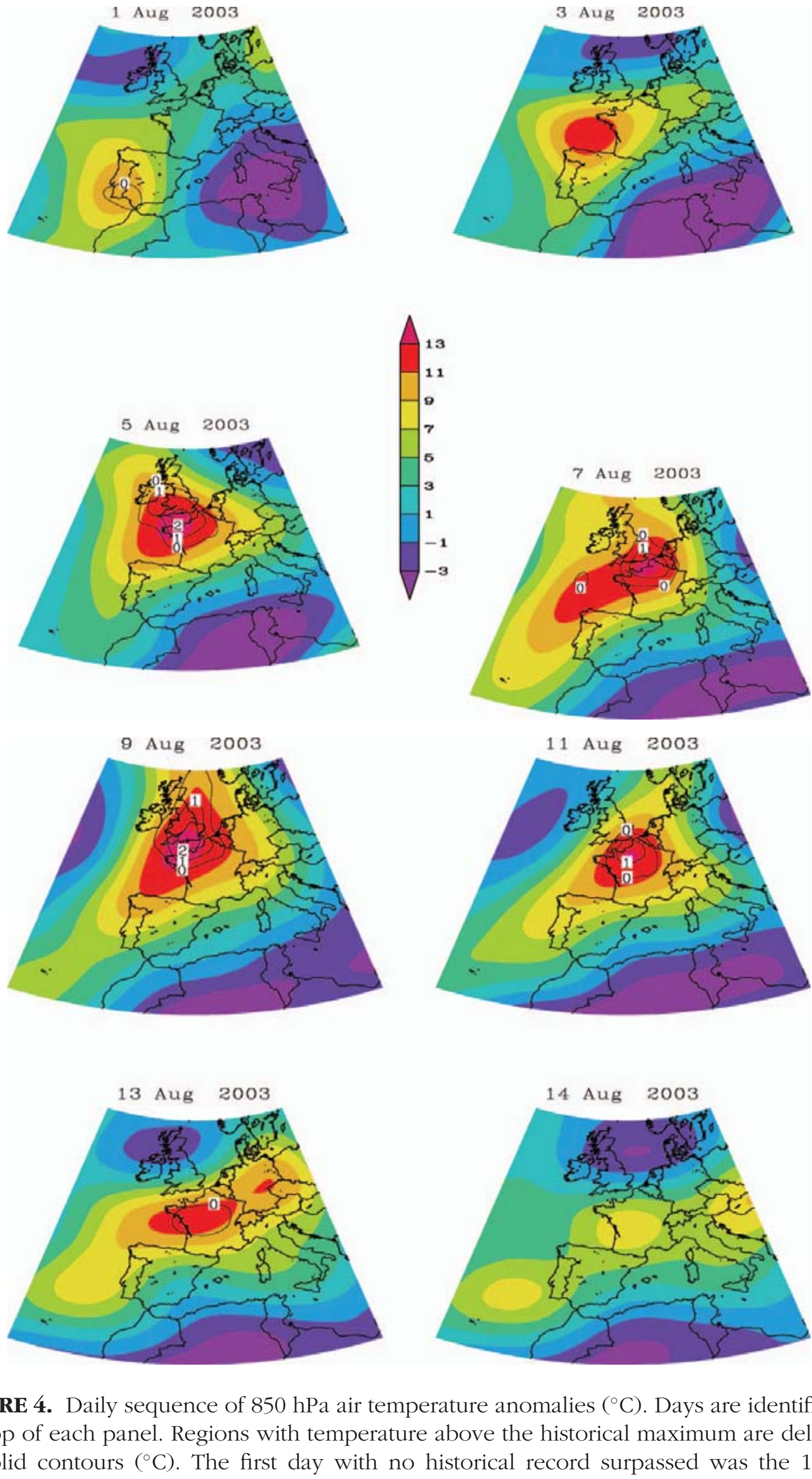

FIGURE 4. Daily sequence of 850 hPa air temperature anomalies (°C). Days are identified on the top of each panel. Regions with temperature above the historical maximum are delimited by solid contours (°C). The first day with no historical record surpassed was the 14th of August. All data from NCAR/NCEP reanalyses.

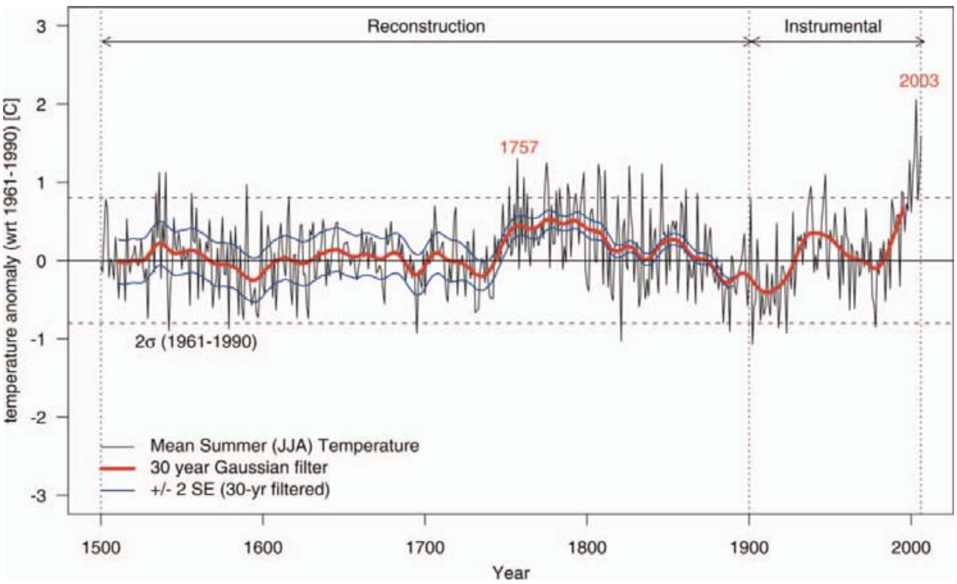

FIGURE 5. Summer (JJA) average mean European temperature anomaly (relative to the 1961 to 1990 reference period) time series from 1500 to 2006 (Luterbacher et al., 2004; Xoplaki et al., 2006), defined as the average over the land area 25°W to 40°E and 35°N to 70°N (thin black line). The values for the period 1500 to 1900 are reconstructions, data from 1901 to 2002 are derived from Mitchell and Jones (2005), data from 2003 to 2006 stem from Goddard Institute for Space Studies (GISS) NASA surface temperature analysis (Hansen et al., 2001). The thick red line is a 30-year Gaussian smooth. Blue lines show the ±2SEs of 30-yr Gaussian filtered reconstructions. Dashed horizontal lines: 2 SD of 1961–1990 period.

Taking into account associated uncertainties in the uncalibrated variance within the 20th century, it turns out that the summer of 2003 at continental scale is extremely likely the hottest for at least half a millennium. There is past seasonal climate information from Europe covering more than half a millennium that can provide information on how unusual the summer of 2003 was in context of the last millennium. Shabalova and van Engelen (2003) have used a combination of long instrumental time series and documentary proxy to reconstruct summer (and winter) temperature for the Low Countries back to 764 (with gaps until around the 13th century). The summer of 2003 seems to be unusually warm; however, several summers, such as 1420 or 1540 and a few others, were as warm as or even warmer than 2003. This is not surprising, as the Low Countries were not in the center of the anomalies during summer 2003.

French records of grape-harvest dates in Burgundy (northeastern France; see Le Roy Ladurie et al., 2006) were used to reconstruct spring–summer (April–August) temperatures from 1370–2003 (Chuine et al., 2004). It has been found that the summer of 2003 represents an unprecedented event in the context of the last 633 years. Similarly, Menzel (2005) concluded that the summer of 2003 was outstanding and exceeds the second hottest summer of 1947 by around 0.5°C. Meier et al. (2007) reconstructed April to August temperature back to 1480 based on grape harvest data from Switzerland. Büntgen et al. (2006) estimated April–September temperatures back to 755 using 180 tree-ring maximum latewood density series from the Swiss Alps. Both studies conclude that the summer of 2003 is exceptional in the context of the past centuries. However, due to the uncertainties in both reconstructions (see Büntgen et al., 2006; Keenan, 2007; Meier et al., 2007; Menzel, 2005), an absolute statement if the summer of 2003 was the warmest at local to regional scale is not possible.

CONTRIBUTING FACTORS

As it will be shown in the following sections, some of the most pronounced impacts of the EHW03 occurred at sub-monthly time scales, particularly those related with health and forest fire activity. However, the summer of 2003 was exceptional from a seasonal perspective (e.g., Luterbacher et al., 2004; Schär et al., 2004,). Recently, several authors have looked at the large-scale forcing mechanisms that were fundamental to help attaining such a persistent anomaly throughout a long period (Black & Sutton, 2006; Black et al., 2004; Carril et al., 2008; Cassou et al., 2004; Ferranti et al., 2006; Feudale & Shukla, 2007; Fink et al., 2004; Fischer et al., 2007b; Jung et al., 2006; Ogi et al., 2005; Schär et al., 2004). Among the most likely factors contributing to the EHW03, these authors have considered the following:

- an extremely persistent blocking;
- the northward displacement of the Azores anticyclone and the African ITCZ;
- a strong positive phase of the East Atlantic teleconnection pattern;
- the southward shift of the extratropical storm tracks;
- the strong amplitude of the summer Northern Annular Mode;
- tropical Atlantic anomalies in the form of wetter-than-average conditions in the Caribbean basin and the Sahel;
- the anomalously clear skies and the downward net radiative fluxes;
- the prolonged high sea surface temperatures (SST) in the northern North Atlantic and the Mediterranean; and
- the intense negative soil moisture anomaly in central Europe and the resulting feedback mechanism.

Naturally, these factors do not act independently and are also related to the monthly climatic anomalies observed for the previous winter and spring months, as already described. Here we analyze those factors that we believe contributed most significantly to the outstanding amplitude of EHW03.

Therefore, we provide an additional insight into the potential role played by three of them—namely, the blocking activity, the soil moisture deficit, and the persistent high SST values.

Atmospheric Circulation

During the months of May and June, parts of northern Europe and Scandinavia were under the influence of low-pressure systems (negative SLP anomaly; see Figure 3) responsible for higher than usual precipitation slightly offsetting the dry conditions in this sector. However, over central and southern Europe, the summer months (JJA) were characterized by extremely hot (see Figure 2) and dry (see Figure 3) conditions induced by an intense meridional circulation, which has been associated with stationary blocking patterns, particularly for the months of June and August (Beniston & Díaz, 2004; Cassou et al., 2004; Ogi et al., 2005; Trigo et al., 2005). This positive height anomaly in the mid-troposphere was however not detectable near the surface over Central Europe. It is suggested that this absence of a positive SLP anomaly in JJA 2003 is, to some extent, due to a heat low mechanism, reducing SLP over the extensively heated continental surface (Fischer et al., 2007b). From a hemispheric perspective, the atmospheric pattern in the second half of summer 2003 was dominated by the summer Northern Annular Mode (NAM), with the corresponding index abruptly increasing into large positive values between mid-July and early August (Ogi et al., 2005). According to these authors, the intense meridional flow components associated with the heat wave over Europe also induced much cooler conditions over Japan. However, the NAM index was nearly neutral in the first phase with prominent anticyclonic circulation anomalies in June 2003.

Summing up, the summer of 2003 was characterized by the presence of consecutive episodes of intense anticyclonic anomalies with strong meridional air flow components. The term blocking has been used repeatedly in previous studies to define these synoptic patterns associated with particularly high geopotential height anomalies over North-Central France, which led to the EHW03 (Ogi et al., 2005; Trigo et al., 2005; Vautard et al., 2005). To evaluate the importance of the different blocking episodes during summer 2003 in a longer context, we have used a recently developed NH blocking climatology (Barriopedro et al., 2006). For a certain longitude, a blocking event can be identified when the 500-hPa height difference between 40° and 60°N is negative over 30° in longitude and during five or more days and, simultaneously, a negative height gradient northward of 60°N is recorded. Based on this approach, we have computed the longitudinal distribution of frequency of blocking days during the consecutive periods 1–15 June and 16–30 June (not shown), 1–15 July, 16–31 July, 1–15 August, and 16–31 August, and compared with the respective 15 days climatologies for the

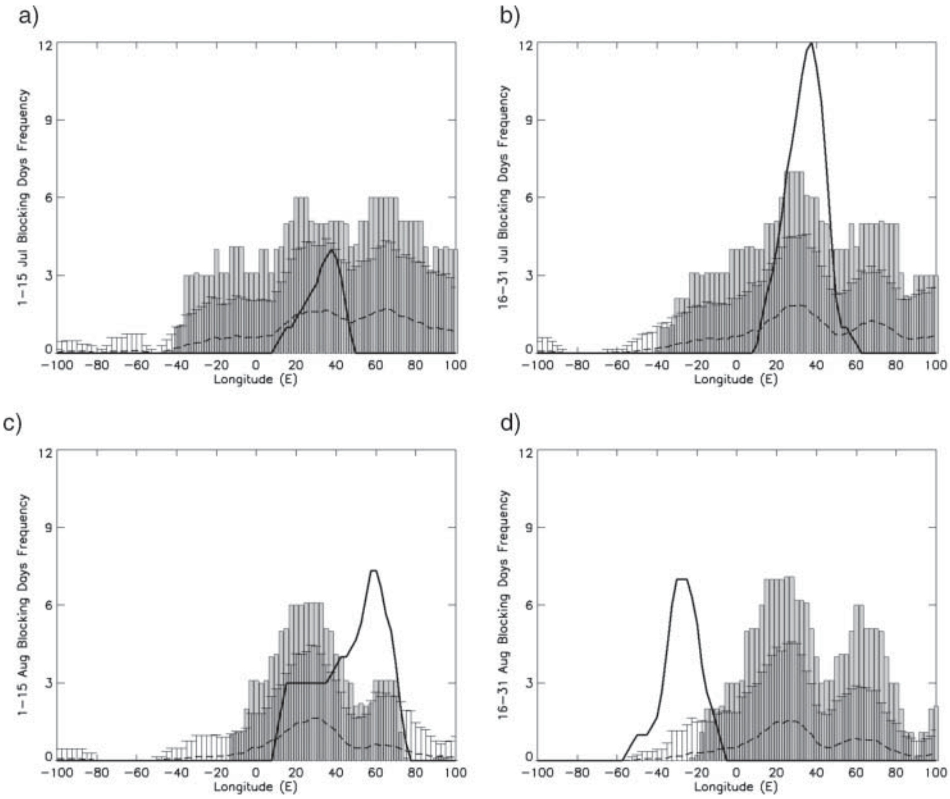

FIGURE 6. Longitudinal distribution for the frequency of blocked longitudes in July and August 2003 (thick solid lines) and the averaged distribution for the 1948–2005 period (dashed lines). Vertical lines (bars) denote the 1.0-sigma level deviation from the climatological mean (the range between the 10 and 90 percentile levels): a) 1–15 July; b) 16–31 July; c) 1–15 August; d) 16–31 August. Data from NCEP_NCAR reanalysis.

period 1948–2005 (see Figure 6). It becomes obvious that the period extending between July 16 and August 31 shows well above average blocking frequencies, though with two different patterns: between July 16 and August 15, the blocking showed a strong omega type and was located eastward of 20°E (figures not shown). Conversely, in the second half of August, the blocking pattern was located further west (Atlantic) and east (Russia) both at high latitudes and showed a diffluent configuration. It should be noticed that previous studies on the climate impact of blocking episodes in Europe have concentrated their analysis on blocking patterns centered either over the Atlantic or Western Europe (e.g., Rex, 1950; Trigo et al., 2004). However, Figure 6c shows that anomalous blocking during the first half of August was located eastward of this sector. Consequently, the blocking shown in Figure 6 for the August 1–15 period should not be mainly responsible for the EHW03. In agreement with other previous studies (e.g., Black et al., 2004), the northerly displacement of the Atlantic Subtropical High shown in Figure 4 is a more likely contributing mechanism than a blocking in the sense defined by Rex (1950).

Soil Moisture

Several studies (e.g., Black et al., 2004; Ferranti et al., 2006; Fischer et al., 2007a, 2007b) suggest that the anticyclonic circulation anomaly alone cannot account for the extreme extent of 2003 summer temperature anomalies. Thus, they suggest an important contribution of land surface-atmosphere feedback mechanisms to the amplification of the heat wave. As seen in Figures 2 and 3, large sectors of Europe suffered from a persistent late winter and spring drought, before even reaching the summer heat wave event. Over large parts of Central Europe, average precipitation was reduced by more than 50% in the four months between February and May 2003 (Fischer et al., 2007a). Observations and regional climate simulations show that persistent surface net radiation excess and the early vegetation green-up (Zaitchik et al., 2006) during the same period resulted in enhanced evapotranspiration and thereby contributed to rapid soil drying (Fischer et al., 2007b). As there is no dense observational soil moisture network in Europe, we here show monthly terrestrial water storage anomalies from the basin-scale water balance (BSWB) data set (Hirschi et al., 2006a, 2006b) and from the Gravity and Recovery and Climate Experiment (GRACE) satellite program for the years 2001–2003 (see Figure 7a). The anomalies are averaged over the four catchments including Rhone, Loire, Rhine, and Elbe outlined in Figure 7b. Figure 7a clearly shows

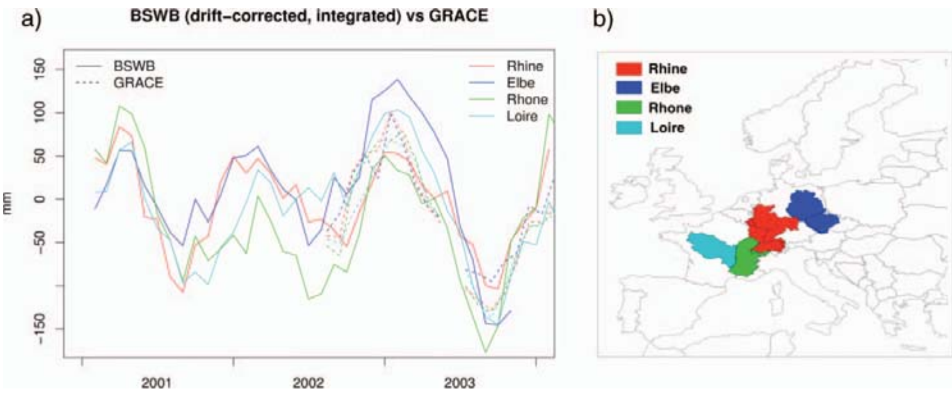

FIGURE 7. a) Monthly terrestrial water storage anomalies from the basin-scale water balance (BSWB) data set (Hirschi et al., 2006a, 2006b) and from the Gravity and Recovery and Climate Experiment (GRACE) satellite program for the years 2001–2003 (redrawn after Hirschi et al., 2006b). The anomalies are averaged over the four catchments Rhone, Loire, Rhine, and Elbe outlined in (b). The GRACE-derived absolute terrestrial water storage estimates are obtained from the University of Colorado GRACE data analysis (CSR product).

very low terrestrial water storage contents in all four catchments during summer 2003 (in both BSWB and GRACE data) with respect to the years 2001 and 2002. While terrestrial water storage values were relatively high at the beginning of 2003 due to heavy precipitation in summer and autumn of 2002 (e.g., Elbe flooding), they decreased very rapidly in the period February–August, resulting in very dry conditions during the entire summer of 2003. The soil drying in 2003 exceeded the long-term average by far, except for the Rhine catchment, for which the estimates for summer 2003 are comparable with the relatively dry summer 2001.

Fischer et al. (2007a) analyzed the contribution of the anomalous land surface conditions to the extent of the 2003 temperature anomalies. They compared the temperature anomalies in a pair of regional climate model simulations with a fully interactive land surface scheme (coupled simulation) and with prescribed soil moisture (uncoupled simulation). Figure 8 shows the seasonal average maximum temperatures in the coupled (left) and uncoupled (right) simulations, which are both driven with observed large-scale atmospheric flow and SSTs (ECMWF operational analysis). Given

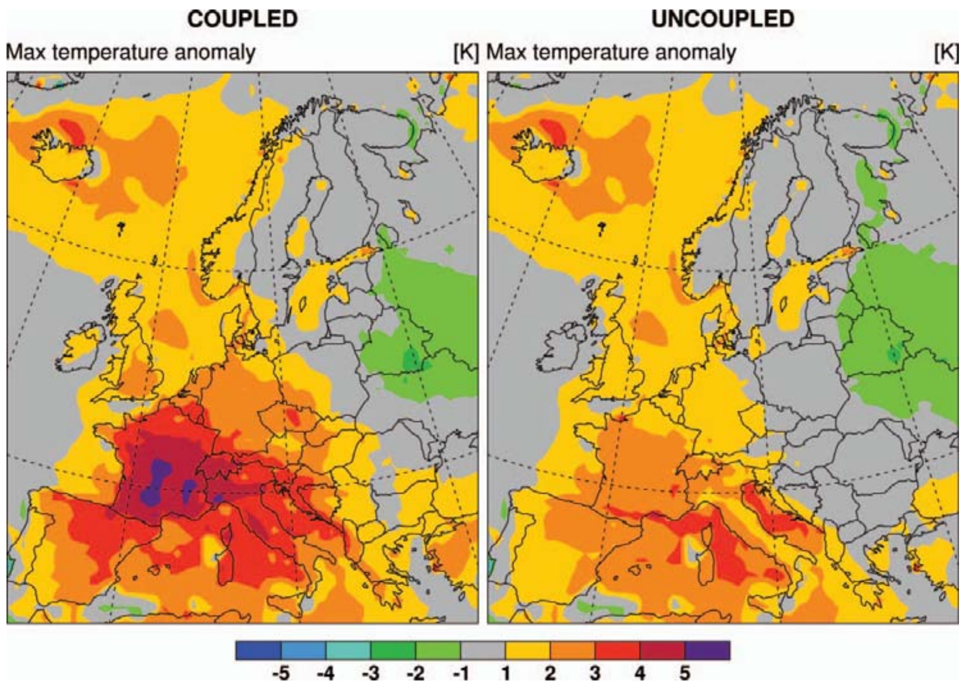

FIGURE 8. Average daily maximum temperature (at 2 m) anomalies in JJA 2003 in a regional climate simulation (CHRM model) with a fully interactive land surface scheme (left) and with prescribed climatological mean soil moisture conditions (see Fischer et al., 2007b, for details on the experimental setup). The anomalies were averaged for summer (JJA) 2003 wrt to a model climatology 1970–2000.

essentially identical continental-scale circulation, however, without anomalous soil drying, the 2003 JJA maximum temperature anomalies would have been regionally reduced by around 1–3°C (40–50% of 2003 summer anomalies). Thus, in the absence of soil moisture feedbacks, the summer of 2003 would still have been warm but much less extreme (Fischer et al., 2007a). The amplifying effect of dry soil conditions has been found to be even more relevant during subseasonal maximum heat wave episodes (e.g., the first half of August 2003) than seasonal average temperatures. Fischer et al. (2007a) demonstrate that land-atmosphere interactions slightly elongated the duration of the subseasonal heat wave episodes and may account for 50–80% of the number of hot days (daily T_{max} > 90th percentile) in JJA 2003.

Soil moisture anomalies affect the surface temperatures mainly through changes in the local surface energy balance (strongly reduced evapotranspiration and latent cooling, which is compensated by enhanced sensible heat flux). In addition to such local effects on the energy budget, drought conditions may have a remote effect on surrounding regions through changes in the continental-scale circulation. Fischer et al. (2007b) suggested that during the summer of 2003, drought conditions have likely amplified and elongated the (preexisting) anticyclonic circulation anomalies, which in turn positively fed back on surface temperatures.

Sea Surface Temperatures

It has been shown that SST monthly means (averaged over the entire Mediterranean basin) from May to August were constantly above the corresponding mean averaged for the previous 45 years (Grazzini & Viterbo, 2003). Although the persistent SST anomalies and the geopotential anomalies over Europe are likely to be closely linked, the exact role of high SSTs within the sub-monthly or seasonal heat wave is not clear (Beniston & Díaz, 2004). It is still under debate whether the SST anomalies over the North Atlantic and the Mediterranean contributed decisively to the EHW03 or if, on the contrary, they were induced by the intense positive tropospheric temperature anomaly.

Here, we extracted monthly SST values from the ECMWF reanalysis (1958–2002) and from the operational analysis (2003). The 1–15 August 2003 SST (see Figure 9) shows large positive anomalies (>3°C) in the western Mediterranean Sea and in a region encircling Scandinavia. Simultaneously, the SLP shows the usual summer configuration of the Azores high, enhanced, and extending further northwest, linking with the high-pressure system located in western Mediterranean. This combination suggests that continental near surface air was heated by anomalous high SST over the Mediterranean. However, this may not be the only contribution of SSTs to the EHW03. Black and Sutton (2006) suggest that the SST anomalies in both the Indian Ocean and the Mediterranean Sea had a significant influence on temperature and

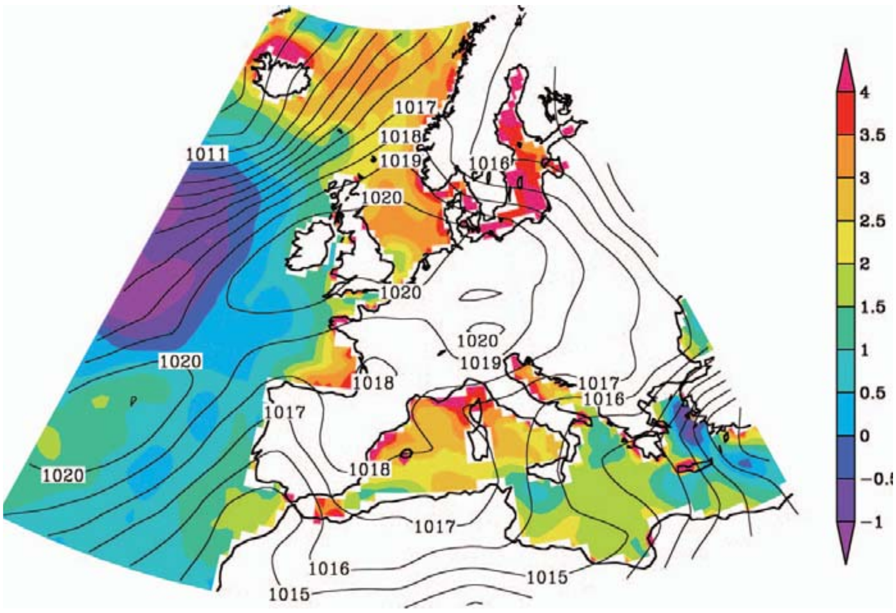

FIGURE 9. Sea level pressure (contour; hPa) and SST anomalies (shaded; °C) for the period 1–15 of August 2003. Climatology for the period 1958–2002. (Data for 2003 from ECMWF analysis while data for the climatological period was extracted from ECMWF ERA-40.)

precipitation throughout the 2003 heat wave. They performed large model ensembles forced with observed and climatological SSTs in the Indian Ocean and Mediterranean Sea. Their findings suggest that the Mediterranean contributed most strongly to the early part of the 2003 heat wave and that the Indian Ocean enabled the positive temperature anomalies to persist well into August. These findings are consistent with Feudale and Shukla (2007), who suggest that global SSTs were responsible for the persistent anticyclonic simulation over Europe. Using AGCM experiments, they showed that by prescribing Mediterranean SST anomaly only, the upper level anticyclone over central Europe could be simulated, though less well than if the observed global SSTs are used.

Ferranti and Viterbo (2006) and Jung et al. (2006) challenge these results, suggesting that the enhanced SSTs had only a marginal influence on the mid-tropospheric dynamical circulation and temperature in Europe. They suggest that the SST anomalies rather followed the tropospheric temperature signal. Ferranti and Viterbo (2006) performed two simulations, one forced with observed SSTs and one with climatological mean SSTs, to analyze the SST's contribution to the EHW03. They found that the influence of soil dry anomalies on 850-hPa temperature is one order of magnitude larger than the influence of the SST anomalies. Jung et al. (2006) performed a sensitivity experiment with the ECMWF forecast model and concluded that the warm

Mediterranean had played a minor role, if any, in maintaining the anomalous atmospheric circulation as observed in summer 2003.

However, it might well be that the currently available seasonal forecasting models are not able to take all complex ocean–atmosphere interactions properly into account (André et al., 2004). When analyzing the failure of different models to forecast the EHW03 at seasonal scales, André et al., (2004) identified a strong SST anomaly over North Atlantic, which started in April 2003 and reached its maximum intensity in July. This SST anomaly (see their Figure 5) was negative for a very large zone from Newfoundland to Ireland, and approximately from 40° N to 55° N, with positive values around it, particularly from Spain toward the southwest up to 50° W. The mechanisms that could link this SST anomaly to the geopotential anomalies during the EHW03 are not fully understood and may involve more complex ocean–atmosphere interactions, such as the interplay between SST anomalies, the position of the ITCZ, and atmospheric teleconnections.

IMPACTS OF THE EHW03

The combination of anomalously high temperatures over most of Western Europe and the associated drought induced a number of health, ecological, societal, and economic impacts (Munich Re, 2004; UNEP, 2004). By far, the most important one was the excessive elderly mortality recorded in several countries across Europe. The environmental and ecological impacts included forest fires, increased pollution, loss of livestock, wilted crops, and loss of forest cover and wildlife (UNEP, 2004). The economic losses associated to EHW03 have been estimated as exceeding US$ 10 billion, with more than 1 billion Euros due to forest fires in Portugal (Munich Re, 2004). Other sources estimate losses of 13.1 billion Euros due to forest fires and drought in the European Union (COPA-COGECA, 2003). These estimations included life insurance payments for heat wave and wildfire deaths; property damage and direct health costs, including hospital stays, clinic treatments, and ambulance rides; livestock and crop damages; fire and timber losses; and hydroelectric power restrictions. Electricity prices rose above 100 Euros/MWh (Fink et al., 2004), and most of the French nuclear power plants suffered from overheating, which lead to interruptions of power. The following sections discuss in detail the most relevant impacts: health, forest fires, plant productivity, air pollution, and alpine ecosystems, located in the core of the temperature anomalies region.

Health

France was the country that experienced the greatest increase in mortality due to the 2003 heat wave. From 4th to 13th August, the ambient temperatures were totally unusual, in terms of their amplitude, but also of their persistence over time. In the time interval that spans from 1st to 20th August, mortality rose by 60% when compared to the average values observed for the same interval in the 1999–2002 period, a rise that translated into 14,802 additional deaths (Fouillet et al., 2006; Poumadere et al., 2005; Valleron & Boumendil, 2004). The increase in mortality and morbidity was probably due to a combination of extreme temperatures and poor air quality, mostly associated to high ozone levels (see Vautard et al., 2007). The vast majority of these extra deaths corresponds to the elderly population that, as usual, were hit hardest (e.g., Pellerin & Hamard, 2003). Thus, in the over-75 age group, there was a 70% rise in mortality compared to the reference period (1946–2002). This rise was also considerable in the 45–74 age group, with an increase of 30%. While it is difficult to ascertain whether an increase took place in the under-45 age group, it nevertheless seems clear that the heat wave had no effect on mortality among those under the age of 15 years. A breakdown by sex showed an 80% increase among women (9,510 deaths) versus 5,292 deaths among men (Hémon et al., 2003). This observed excess mortality varied from place to place, and was closely linked to the number of days with maximum temperatures above 35°C and minimum temperatures above 20°C. Accordingly, excess mortality figures ranged from 30% of the usual mortality structure for places having just one day of extremely high temperatures, to 50% for places that registered 2–5 days of excess heat, to as high as 80% for places experiencing 6 days or more, a finding that would explain increases as disparate as those recorded for relatively close cities such as Lille (4%) and Paris (142%) (Vandetorren et al., 2004).

For additional information on specific health issues related to the 2003 heat wave in France, the reader is referred to Cassadou et al. (2004), Misset et al. (2006), and Pascal et al. (2006).

This pattern described for excess mortality in France was qualitatively similar to that observed for other areas across Europe, though the quantitative repercussion varied considerably from country to country. Thus, in the case of Spain, increased mortality during the months of June, July, and August stood at around 6,500 deaths more than expected, based on the modeling that was done for the baseline 1990–2002 period, and can be assumed to furnish information on expected mortality for this period (Martínez et al., 2004). Analysis of the heat wave in Spain from the standpoint of a temperature-mortality relationship revealed a pattern very similar to that reported for France (Díaz et al., 2006b). In the case of Spain, a threshold temperature was established for maximum temperature, which coincided with the 95th percentile of the series of daily maximum temperatures in the summer months (García-Herrera et al., 2005). This local threshold temperature served to define a heat wave intensity index that took into account the number of days on which the threshold was exceeded, and also the accumulated magnitude of this exceedance. The results obtained showed a logarithmic association between the index value and the increase in the mortality rate (Díaz et al., 2006a). As in the case of France, the largest excess mortality was observed for women over the age of 65 years and for circulatory and respiratory diseases, a finding that agreed with earlier studies undertaken in Spain (Díaz et al., 2002a, 2002b). Again, similarly to the situation described for France, a relationship, though of lesser intensity, was also detected between mortality and temperature in the 45–64 age group (Díaz et al., 2006b). However, no statistically significant link could be established for subjects under the age of 10 years (Díaz et al., 2004).

In the case of Portugal—despite Lisbon being one of the few European cities that had a heat-wave prevention plan, the so-called ÍCARO Project (Nogueira & Paixão, 2008)—the observed excess versus the expected mortality (based on the mean for the 2000–2001 period) occurred from 1st to 15th August, with a 43% increase (1,953 persons). This figure is significant but substantially lower than that obtained for France and hides an asymmetrical gender impact in mortality, with a 27% increase for men (636 deaths) and 61% increase for women (1,317 deaths). Again, the greatest excessive mortality took place among the over-75 and 65–74 age groups. Data for Italy, corresponding to the cities of Bologna, Milan, Rome, and Turin, are compatible with the earlier estimate that 3,134 excess deaths occurred in Italy's 21 regional capitals during the period that spans between 1st June–15th August (Kovats et al., 2004b; Michelozzi et al., 2005). Of these, 92% occurred among subjects over the age of 75 years (Conti et al., 2005). Nevertheless, the Italian National Institute of Statistics reported an excess of 19,780 deaths countrywide during June–September 2003 versus 2002 (ISTAT, 2004). A strong association between daily mortality and the humidex index (a combined index of temperature and humidity) was observed, which was not the case in Iberia.

In England and Wales, definitive mortality data was evaluated for the period 4th–13thAugust 2003, when ambient temperatures were compared to averages for the same period in the years from 1988 to 2002. Overall, there were around 2,139 (16%) excess deaths accounted for this 10-day period. Again, elderly people over the age of 75 were affected the most (Johnson et al., 2004). An estimated 7% increase in all-cause mortality occurred in Switzerland from June to August 2003 (975 deaths; Grize et al., 2005). In the Netherlands, total excess mortality in the period June–September 2003 was estimated at 1,400–2,200 deaths, implying an increase of approximately 3–5% over the number usually recorded for this period. The number of excess deaths during the peak of the heat wave, between 13th July–13th August, is likely to be estimated around 500. The effect of heat on mortality showed a strong increase with age. The fact that the maximum temperatures were lower than in some other European countries and occurred in less heavily populated areas may have led to mortality figures that were relatively less dramatic (Fischer et al., 2005; Garssen et al., 2005).

Reports elsewhere indicate that approximately 1,250 heat-related deaths occurred in Belgium during the summer of 2003 (Sartor, 2004). Germany registered an excess mortality of 7,000 persons during the entire summer of 2003 (Schär & Jendritzky, 2004) and 1,410 persons during the period 1st–24th August in Baden-Wurttemberg (Kosatsky, 2005).

In light of the above, it thus seems clear that the summer 2003 heat wave in Europe had major effects on the health of the population, and that, overall, the magnitude of these effects surpassed anything that had occurred in Europe in previous heat waves. Although the individual characteristics of each place and the locally registered temperatures distribution imply that the number of persons affected may vary from one place to another, the existence of common behavior patterns is nonetheless evident. Hence, the influence of temperature proved decisive in respect to the increased mortality detected one to two days after the rise in such temperatures. The diseases and disorders associated with the excess mortality appear to be mostly circulatory- and respiratory-related, with age being a decisive risk factor, so the maximum increases were observed among the persons over 75. Insofar as sex was concerned, all of the studies conclude that the effect on women was clearly larger than that on men. Other risk factors were also detected, such as suffering from certain type of psychiatric disorders or living alone in the case of elderly subjects. Table 1 provides a summary of the deaths attributed to EHW03 in every country. It also shows the period when mortality was estimated and several thermal indices that estimate the intensity of the heat wave in every country. However, these numbers underestimate significantly the cumulated impact in excessive mortality for the entire summer 2003, as some countries (particularly in Italy) have registered excess mortality continuously from June to late August. Moreover, these figures might also underestimate the real impact, as a significant portion of those who survived from the heat stroke might sustain severe neurological damage resulting in increased mortality up to one year after exposure (Bouchama, 2004).

This excess mortality evidently entailed an increased demand for hospital care (Johnson et al., 2005), a greater incidence of demand for healthcare in the above-mentioned diseases (Kovats et al., 2004a) as underlying causes of death, and a higher incidence of admissions to the surgical Intensive Care Unit (e.g., Dhainaut et al., 2004; Johnson et al., 2005).

It has been shown in previous studies on the excessive mortality impact of heat waves that the first victims in these events are usually the most vulnerable. Furthermore, it has been shown that in the immediate period following the heat wave the number of deaths is *lower* than what would have been expected. This is known as the *harvesting effect*, as the expected overall mortality rates for a given period are averaged out (Kalkstein 1993, 1995). However, it must be noted that studies made in France (Le Tetre et al., 2006), the Netherlands (Garssen et al., 2005), and Switzerland (Grize et al.,

TABLE 1. Estimation of deaths associated to the EHW03

Country	Number of deaths	Calculation period for deaths	Maximum heat wave temperature	Threshold temperature for increased mortality	Source
France	14,802	4–13 August	T_{max} > 40°C (27 stations)	T_{max} > 35°C and T_{min} > 20°C	Poumadere et al., 2005; Valleron and Boumendil, 2004
Spain	6,500	June–August	T_{max} > 40°C (19 stations)	T_{max} > 95th percentile	Martínez et al., 2004
Portugal	2,099	30 July–15 August	T_{max} 45.4°C (Beja)	T_{max} > 32°C	Botelho et al., 2004; Nogueira and Paixão, 2008
Italy	3,134	1 July–15 August	T_{max} 40°C (Milan)	Apparent T_{max} > 90th percentile annual series	Kovats et al., 2004a; Michelozzi et al., 2005
England and Wales	2,139	4–13 August	T_{max} 31.5°C (Preston-London-Bristol)	T_{max} > 25°C	Johnson et al., 2004
Switzerland	975	June–August	T_{max} 41.5°C (North of Alps)	T_{max} > 35°C and T_{min} > 20°C	Grize et al., 2005; Thommen Dombois and Braun-Fahrländer, 2004
The Netherlands	1,400–2,200	June–August	T_{max} 35°C	Weekly mean T_{max} >16.5°C	Fischer et al., 2005; Garssen et al., 2005
Germany	7,000	June–September	T_{max} 40.4°C (Bavaria)	Perceived temperature	Schär and Jendritzky, 2004
Belgium	1,250	July–September	T_{mean} 28.9°C (Brussels)	—	Sartor, 2004

For every country, the estimated number of deaths is provided jointly with the period used for the estimation and the maximum and threshold temperatures.

2005) show that this effect may have been notably absent during the EHW03 contradicting earlier analysis (Valleron et al., 2004).

Forest Fires

The widespread nature of the EHW03 implied a large amount of total burned area (739,000 ha) for the five southern European countries prone to summer fires, namely, Greece, Italy, France, Spain, and Portugal (EC, 2004). Nevertheless, since 1980, when aggregate values of total burned area for these countries became available, two previous years have seen higher amounts (1985 and 1989). However, the relative importance of the year 2003 varies considerably between these countries, for example in France the final figure for 2003 (73,000 ha) is similar to the previous maxima observed in the consecutive years of 1989 and 1990. However, in Portugal the 2003 fire season represents an outlier year in almost every sense, in particular considering the outstanding total burned area and also the large concentration of major fires within the central region of Portugal. The area burned between 1st August and 7th of August was roughly 200,000 ha, and estimates for the end of season total burnt area (431,000 ha) represent an outstanding figure of roughly 5% of the Portuguese territory (Trigo et al., 2006). Like most Mediterranean countries, fire activity in Portugal is highly concentrated in the summer (JJAS) months (>90% of total) and presents large values of spatial and temporal variability of burned area (Pereira & Santos, 2003, Pereira et al., 2005). To put the year 2003 extreme event in perspective, the inter-annual variability of summer burned area between 1980 and 2004 is shown (see Figure 10). Previous maximum values observed in the years of 1991, 1995, 1998 and 2000 were dwarfed by the outstanding value associated with the summer 2003 event (Trigo et al., 2006).

Mapping of the summer 2003 wildfires in Portugal was assessed through different sensors and satellite platforms (European Commission, 2004; Trigo et al., 2006). TERRA-MODIS burned area maps were produced at seven dates during the summer of 2003, respectively, the 4th and 17th of July, the 1st and 14th of August, the 4th and the 14th of September 4, and the 4th of October. Based on these seven consecutive images, we may observe the spatial and temporal evolution (see Figure 11) of burned area throughout the summer. Despite the irregular intervals between the seven images, the concentration of burned area between the 2nd and the 14th of August (red color) is striking, with late August (yellow) and early September (brown) also presenting important but much smaller values.

Impact on Vegetation Productivity

Considerably low levels of water availability for plant roots were bound to produce a large negative impact on vegetation health. In a recent major study

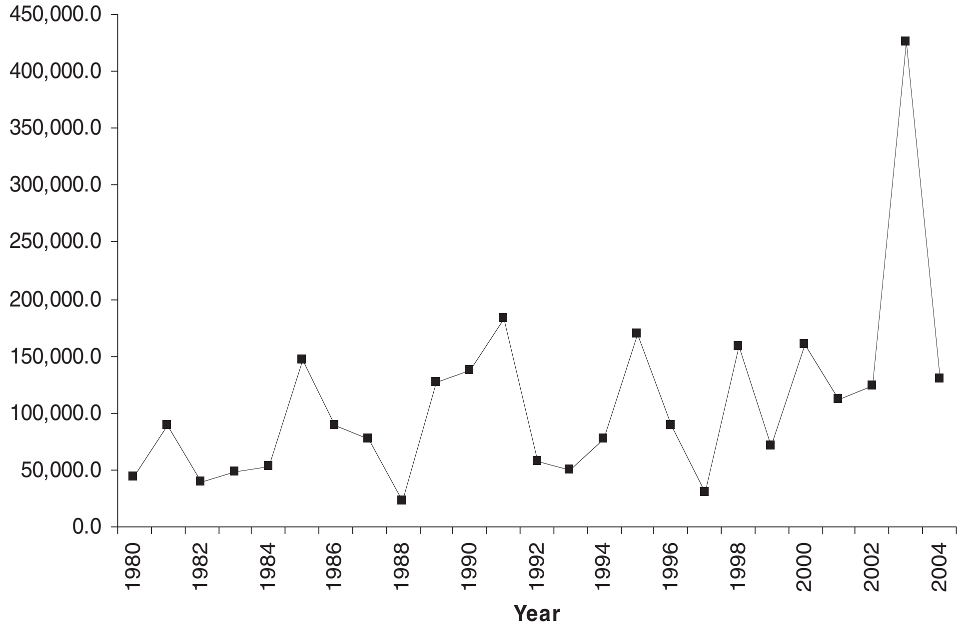

FIGURE 10. Annual values of total burnt area between 1980 and 2004 compiled by the Portuguese Forest Institute (DGRF). The wildfire scars were evaluated based on visual interpretation and on-screen digitizing of MODIS red-green-blue (RGB) color composites, based on channel 7 (2.105 μm–2.155 μm), channel 2 (0.841 μm–0.876 μm), and channel 1 (0.620 μm–0.670 μm). The spatial resolution of channels 1 and 2 is 250 m, while that of channel 7 is 500 m. The minimum mapping unit (i.e., the size of the smallest fire scars mapped) is 100 ha.

that employed a terrestrial biosphere simulation model, Ciais et al. (2005) have estimated a 30% reduction in gross primary productivity over Europe. According to these authors, this decrease resulted in a strong anomalous net source of carbon dioxide (0.5 Pg C/yr) to the atmosphere and reversed the effect of four years of net ecosystem carbon sequestration. Moreover, taking into account historical records of crop yields suggests that such a reduction in Europe's primary productivity is unprecedented during the last century (Ciais et al., 2005). Jolly et al. (2005) show that this reduction in productivity should have occurred below 1400m asl, while vegetation above that altitude should have experienced an increase in productivity due to extended growing season and water stress similar to average conditions during 2003.

To assess the response of the vegetation, we used Normalized Difference Vegetation Index (NDVI) fields derived from images acquired by the VEGETATION instrument onboard satellite SPOT. Monthly average values were computed from the original 10-day values available between 1999 and 2004, for a European window (latitude 35.72°N to 58.22°N, longitude 11.00°W to 23.20°E). Then, we obtained long-term monthly averages of NDVI for the period 1999–2004 (excluding 2003). Figure 12 shows the anomalies of NDVI

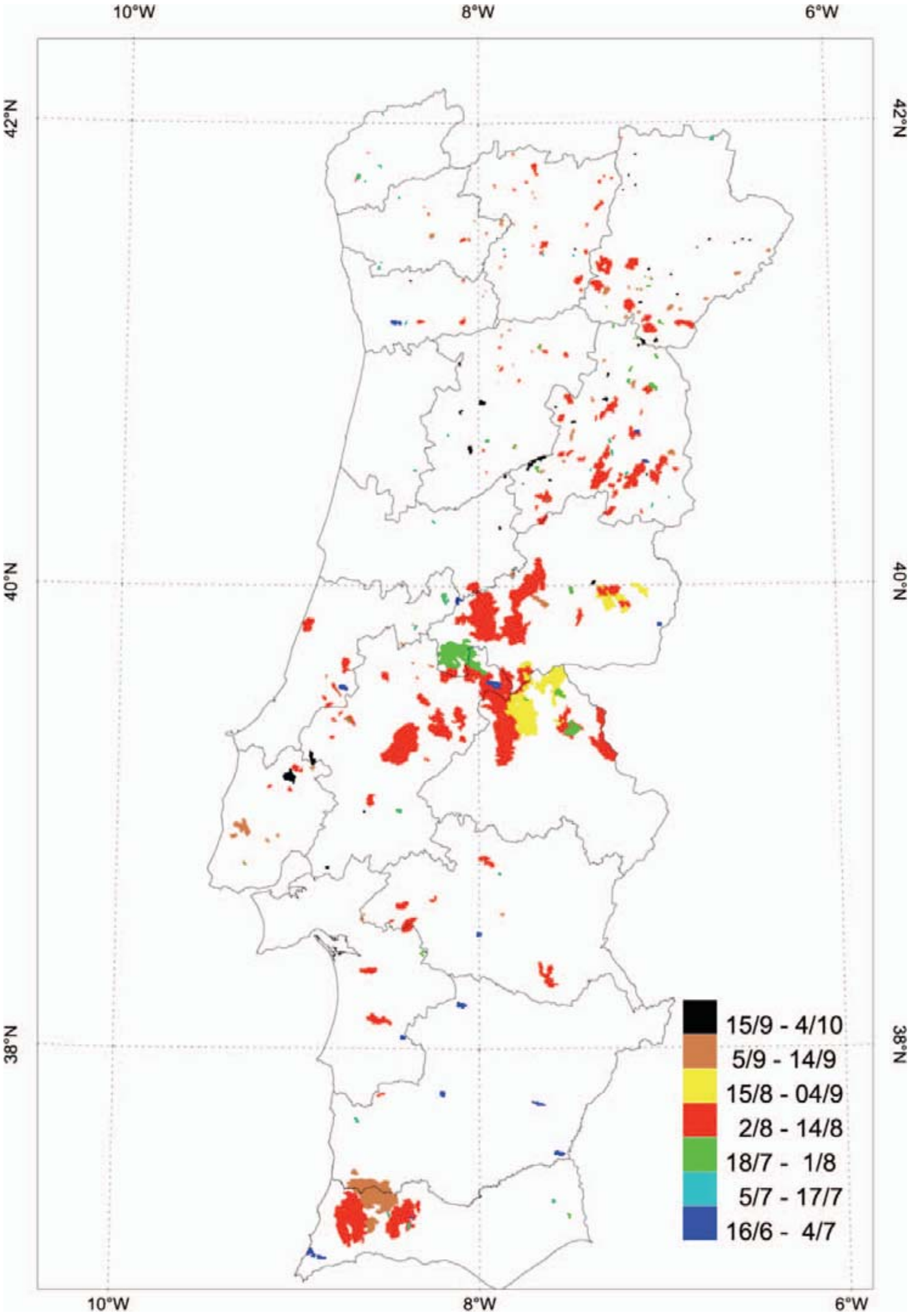

FIGURE 11. Burnt area evolution throughout the summer 2003 using seven consecutive images from TERRA-MODIS.

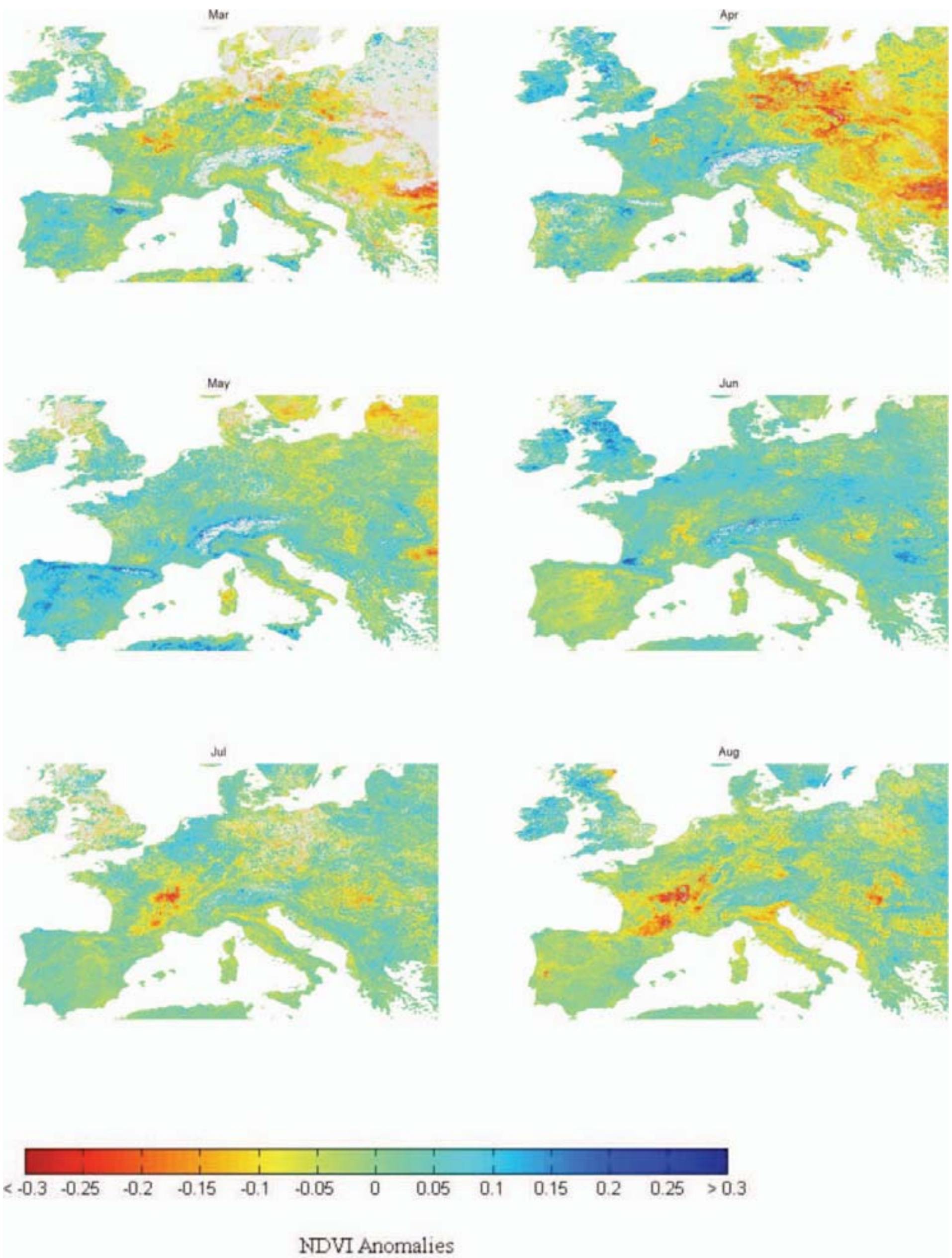

FIGURE 12. Monthly anomalies of NDVI between March and August 2003. The anomaly was calculated with respect to a base period obtained for the years 1999–2004 (excluding 2003). Negative (positive) anomalies corresponding to lower (higher) than average NDVI values are shown in warm (cold) colors. Data from VEGETATION instrument on board of SPOT satellite.

monthly values for 2003 between March and August 2003. Above-average values of NDVI are clearly visible in cold colors, while deficits of NDVI are represented in warm colors. All pixels contaminated by clouds, snow, and ice are shown in grey. The evolution of the regional patterns is well associated with the corresponding climate anomalies described in Figures 2 and 3. In fact, the quasi-stationary anticyclonic conditions over Scandinavia between February and April (see Figure 2) implied substantially lower than average precipitation values throughout northern France, Germany, Poland, and Caspian Sea regions (see Figure 3), depriving the necessary water for plant growth in early spring (Fink et al., 2004). It should be stressed that, at these latitudes and time of the year, the maintenance and growth of vegetation is typically controlled by water availability (Gobron et al., 2005). This fact helps to explain the generalized extent of negative NDVI anomalous values in April over much of Eastern Europe (see Figure 7). Interestingly, the state of the vegetation health improved in the following months of May and June, with less widespread negative anomalies of NDVI, only to be pushed again to new stress records (Ciais et al., 2005) during July and August as a consequence of very hot and dry air masses. In late August, minimum values of NDVI could be found over central and southern France and around the Alpine region (see Figure 12) (i.e., directly associated with the spatial extent of the relatively short-lived EHW03).

Agriculture

According to COPA-COGECA (2003), the year 2003 was poor for agriculture in the European Union, especially in Italy, Germany, Austria, Spain, France, and Portugal. This was due to the combined effect of the drought and the excessive temperatures recorded since June, it not being possible to estimate the impact of the short but intense EHW03 period. As a consequence of this combined impact, a large proportion of harvests, productivity, and markets were at risk, and increased production costs were a general phenomenon. The impact presented high regional variability, being larger on the green fodder supply, the arable sector, and the livestock sector, both extensive and intensive (mainly the poultry and egg sector). The fodder deficit varied from 30% (Germany, Austria, and Spain) to 40% (Italy) and 60% (France). The eggs and poultry sector was badly affected in France and Spain. Almost 4 million broilers died in France due to the heat wave, and the poultry flock was reduced by between 15% and 20% in Spain. France showed the largest impact on milk production, with a reduction of 2.65% of estimated for the June to September period. With approximately 186 million tons (MT), the total EU arable sector showed a fall in production of more than 10%. Common wheat (–11% or some 10 MT) and maize (–21% or approximately 9 MT) were the most damaged crops. Over three-quarters of the soft wheat output and some 55% of the maize output lost at community level are attributable to the drought in France, while one-third of the fall in EU maize production is attributable to the decrease of production in Italy. Potatoes production in EU was reduced by around 5%, with Spain (–30%) and Germany (–25%) showing the highest reduction. The impact on wine production was far from homogenous, with a reduction of up to 18% in Italy and France and increases in Portugal (10%) and in Spain (5%). Whereas for berries and wine growth in Switzerland, the conditions had been excellent during 2003, the dry conditions caused profit cuts in arable crops and scarcity in animal feed. In order to mitigate cases of hardship, the Swiss Federation had taken measures to reduce the bottlenecks mainly for animal care (Keller & Fuhrer, 2005).

Ozone and Aerosols

The European Environmental Agency (EEA) collected data from 1805 ozone monitoring sites from 31 countries and concluded that the EHW03 was accompanied by an exceptionally long-lasting and spatially extensive episode of high ozone concentrations (Fiala et al., 2003). The maximum hourly ozone concentration reported in 2003 was 417 $\mu g/m^3$ at a monitoring station close to Marseille in France. The information threshold (hourly average concentrations of 180 $\mu g/m^3$) occurred in 23 countries, and about 68% of all stations reported one or more exceedances with an average of 5.4 exceedances per operational station reported. In fact, the average number of hourly ozone exceedances above 180 $\mu g/m^3$ was higher in the summer of 2003 than in any of the previous 12 years for any monitoring site. According to Ordoñez et al. (2005), in Switzerland, the 2003 summer mean of the daily ozone maxima exceeded the 1992–2002 average by more than 15 ppb, corresponding to five standard deviations, similar to the deviation in surface temperature. The exceedance episodes were mostly concentrated in the great Alpine sector, an area encompassing southwestern France, southeastern Germany, Switzerland, and northern Italy. This is in agreement with the recent findings of Solberg et al. (2008), that the 95th percentiles of daily maximum hourly ozone concentrations in 2003 were higher than in any previous year at many sites. When compared with previous summers, these episodes were much more extended than in any other summer recorded by the EEA. Solberg et al. (2008) also suggest that a number of positive feedbacks between the weather conditions and ozone contributed to the elevated surface ozone, including extended residence time of air parcels in the atmospheric boundary layer and the extensive forest fires on the Iberian Peninsula.

According to the CHIMERE model (Vautard et al., 2005), low to moderate ozone concentration were recorded on the 1st of August, while concentrations surpassed the information threshold in the Ruhr area, northeast France, Paris, and near Marseille in the south of France along the 2nd and 3rd of August. The high-ozone region rotated clockwise from southern Germany (4th of August) to north-central France (6th–7th of August) and then western France (8th–9th of August), associated with an anticyclonic displacement. Simultaneously, another high-concentration area built up over northwestern Europe and stagnated after the 7th of August. An Atlantic cold front displaced eastward the ozone-polluted air masses after the 12th of August. According to Vautard et al. (2005), this episode is very typical for the ozone transport across Europe during summertime ozone episodes: air masses move from one place to another in high-emission areas in northern Europe in a rotating stagnation framework, while southern areas (Marseille, the Po valley, and Genova) do not seem to be connected to this transboundary transport and undergo a more local influence.

It is interesting to analyze the behavior of the variables that contributed to high ozone episodes during the EHW03 (i.e., increased UV radiation, less cloud cover and precipitation, extended residence time in the polluted boundary layer, reduced dry deposition, increased biogenic emissions, and excessive forest fires; see Tressol et al., 2008).

Excessive temperatures were accompanied by an enhanced cloudless sky in France, southern Germany, Switzerland, and northern Italy. It has been estimated that France recorded an increase of almost 1 kWh/m^2 in the monthly mean daily irradiation during August, which was consistently high every day. In fact, there was a reduction of 76% in the irradiation variability with respect to the 1993–2002 average, something unprecedent (Albuisson et al., 2003). This increased temperature and solar radiation, jointly with direct measurements of isoprene (Solberg et al., 2005, 2008), indicate that biogenic emissions in Europe were increased during summer 2003 with a potential for enhanced ozone formation. Regional-scale model calculations indicate that enhanced levels of biogenic isoprene could have contributed up to 20% of the peak ozone concentrations (Solberg et al., 2008).

Due to the high temperature and the precipitation deficit during the previous spring and summer 2003, low vegetation with superficial roots underwent water deficit, leading to an important decrease in ozone dry deposition (Emberson et al., 2000) due to stomata closure of the plants.

Additionally, an episode of a low total ozone column (LOE) over northern Europe during the EHW03 in mid-August 2003, peaking over Scandinavia and the North Sea around 10 August, was recorded (Orsolini & Nikulin, 2005). Low-ozone stratospheric air extended southward from the Arctic toward northern Europe as the large-scale circulation in the lower and mid-stratosphere was perturbed by large-scale waves. Combined with the column ozone subsiding due to anticyclonic conditions, this southward displacement of stratospheric Arctic air led to a column abundance as low as 250 Dobson Units (DU) over the North Sea and parts of Scandinavia (Orsolini & Nikulin, 2005). The low ozone column over North Europe could have a potential effect for the photochemical ozone formation in the lower troposphere during the heat wave by altering the photolysis rate of $O_3 \rightarrow O'D$, which in turn may increase the OH concentration and thereby speed up the general oxidation rate of the troposphere.

Finally, the extensive forest fires described earlier could also have an impact on ozone levels in northern and central Europe. Recent studies have indicated that during summer of 2003, biomass fires burned a large area of Siberia, the largest in at least 10 years (Jaffe et al., 2004; Yurganov et al., 2005), and that the background concentration of both CO and O_3 were enhanced at many sites in the northern hemisphere (Tressol et al., 2008). As evidenced by Hodzic et al. (2006, 2007), due to the extremely high temperatures, the fire-emitted particles were directly injected into the atmosphere up to 3 to 4 km of altitude and were transported from Portugal to northern Europe. Based on the FLEXPART model, Solberg at al. (2005) showed that the air masses located over Belgium originated mainly from the Gulf of Biscay and the western parts of the Iberian Peninsula, close to where the forest fires burned during the first half of August. These results clearly indicate that the forest fires in Iberia during August could indeed have contributed to the peak values of surface ozone observed in Northern Europe. Thus, the 2003 summer is a “field example” of the close link between meteorological conditions, and a secondary pollutant like ozone. Climate model scenarios have indicated that extreme weather events like this may become more frequent in the future. Thus, the effect of future climate change may gradually outweigh the benefit of the emission abatement in Europe for secondary photochemical pollutants (Solberg et al., 2005). According to Vautard et al. (2007), for ozone, the effect of regional reduction of emissions will dominate over summer climate change, but the increase in baseline ozone should significantly raise the mean ozone levels.

Alpine Ecosystems

It has been estimated that Alpine glaciers lost 5–10% of the total mass of the ice cover (Fink et al., 2004; Gruber et al., 2004; Häberli et al., 2005; UNEP, 2004). The freezing limit rose above 4500 masl for 10 days, which resulted in anomalous thawing and degradation of mountain permafrost and thus a destabilization of Alpine rock walls. These extreme conditions caused widespread but relatively small rock falls and increased the accumulation of melt water in lakes precariously located near settlements (Gruber et al., 2004; Häberli et al., 2005). Jankowski et al. (2006) used data from two Swiss lakes to determine the effect of the 2003 heat wave on water temperature and oxygen conditions. Throughout the summer 2003, surface temperature and thermal stability were the highest ever recorded in both lakes. The study of the dynamics of the mollusk populations in the Saone river and two of their tributaries showed that the summer 2003 was the hottest since 1500 (at least), and that the heat wave originated a sudden and dramatic decrease of mollusc spices richness and densities, which was still detected during 2004 (Mouthon & Daufresne, 2006).

The pollen season was shorter but more intense in most of Switzerland, including the Alps, which increased the stress for the allergic population (Gehrig, 2006). The combined effect of drought and heat altered significantly forest pest populations in Europe during 2003, with large differences being observed according to geographical regions and insects feeding patterns. Thus, woodborers infestations showed a significant increase, while defoliators mostly increased during 2004. As a consequence, Germany, Austria and Switzerland reached record levels of infested wood, with significant increases reported also in France and the Czech Republic (Rouault et al., 2006).

SOME LESSONS

As shown in this paper, the summer mean temperatures of 2003 were extremely likely the warmest for more than half a millennium at European and Mediterranean scale (Luterbacher et al., 2004; Xoplaki et al., 2006). However, the most outstanding temperature anomalies and associated impacts on human health and ecosystems occurred during the first fortnight of August (EHW03). It was caused by an anomalously persistent northerly displacement of the Atlantic Subtropical High, rather than a standard blocking pattern as defined by Rex (1950). It seems undoubtedly that this temperature anomaly was amplified by a severe soil moisture deficit originated in the previous months, as a consequence of below average precipitation in the previous winter and spring. While some studies suggest an important role played by high SSTs over the Mediterranean Sea, the North Atlantic and Indian Ocean in the generation and persistence of EHW03, other analysis suggest that SSTs have played a marginal role in this event.

According to Stott et al. (2004), it is likely that anthropogenic warming contributed to EHW03 by doubling its probability of occurrence. Chase et al. (2006) analyzed extratropical tropospheric temperatures since 1979 in the 22°N–80°N region. They show that extreme warm anomalies equally (or more) unusual than the EHW03 occur regularly, being closely correlated with hemispheric and global average temperatures. Different studies suggest that episodes similar to EHW03 may occur more frequently in the future due to global warming. The analysis of EHW03 should help to mitigate the impact of future similar episodes. This could be achieved through the implementation of better forecasting and an improvement of the prevention services. A better characterization of the interactions of the atmosphere with the land surface as well as with SSTs should improve models performance in forecasting this type of events.

Different reports provide some clues on the profile of the victims and the main causes of this unprecedented impact in France (Lagadec, 2004; Ogg, 2005; Vandentorren et al., 2006). The first and strongest finding is that, as described above, age is the most important single factor associated with the excess mortality. The second characteristic of the victims to emerge was that rates of excess mortality were higher for women (70%) than for men (30%), a finding very different to what occurred in the Chicago 1995 heat wave, where rates were twice as high among men (Klinenberg, 2003). The fact that more women were affected than men is partly due to the lower number of men in the elderly population, and partly because older women tend also to suffer more from problems of thermoregulation than men. The third characteristic of the victims is that they were mostly concentrated in urban areas. Additionally, mortality rates for August 4 to 14 doubled both among individuals living in their own home and in retirement homes. In total, 42% of the 15,000 excess deaths registered in France during the heat wave occurred in hospitals, 35% at home, 19% in retirement homes, and 3% in private clinics. The influence of medical care in French nursing homes has been evaluated (Holstein et al., 2005), showing that it helped to limit deaths in the more fragile patients, but paradoxically the less frail made the largest contribution to excess mortality. Thus, specific attention should have been paid to all elderly people and not only to the more frail. It was found that the social class status of the victims was a significant factor, with lower social class groups being more at risk. At the same time, social class status was positively linked to housing with less air-conditioning and fewer rooms, which may have been decisive, as more rooms provide a greater potential to find a cooler place within the home. Other housing characteristics associated with higher death risk were lack of thermal insulation and sleeping on the top floor, close to the roof. Disability was also linked to risk factors, with persons confined to bed or severely disabled being more exposed to risk. Lagadec (2004) and Ogg (2005) have identified that public services also contributed to the excessive mortality: they reacted too late, and the coordination of services for older people was not effective, neither in a preventative role nor in managing the crisis. Mitigation of health impacts should imply improvement of alert systems specifically aimed at the elderly population, improvement of housing conditions to afford higher extreme temperatures, and a better social and health care. According to Cohen et al. (2005), to be successful, these actions ". . . should include health recommendations corresponding to each kind of atmospheric danger. A general incitation to such an approach would help to develop and increase (even in countries, like France, that have not been used to pay consideration to such phenomena) a new culture for meteorological risks." Fortunately, from a public health perspective, the EHW03 has represented a real landmark in a European context. Even when studies addressing the impact of extreme heat on health had been conducted for many years (for example, the review by Basu and Samet covers a total of 98 papers dating from as far back as 1957 to 2002), the excess mortality registered in Europe in the summer of 2003 marks a turning point in the design and implementation of European prevention plans, which until then had been notably absent. Indeed, it can be said that, prior to the summer of 2003, only Lisbon and Rome were provided with genuine heat wave alert systems (WHO, 2004). At present, most European cities possess extreme-temperature prevention and alert plans, which come into operation when weather forecasts indicate the likelihood of the safety thresholds set for the specific locality or town being exceeded. Thus, even when housing conditions will not change dramatically in a near future, the new alert systems and the increased social awareness make highly unlikely that a new heat wave of identical characteristics (intensity and duration) should have a similar impact on human mortality.

This may not be the case for forest fires. In fact, the 2005 and 2006 summers were also characterized by extensive fires in Iberia—particularly in 2005 in Portugal, with the second highest total burned area in this country (338,000 ha), while the summer of 2006 struck the northern Spanish region of Galicia (close to 100,000 ha). According to the European Commission's Forest Fire Information System (EFFIS), 183,987 hectares were burnt in Greece between 24 and 26 August 2007, during the major forest fires that have ravaged that country. This brings the provisional figure to this point in the 2007 forest fire season in Greece to approximately 270,000 ha. Over the long term, the prevention and management of the different impacts in future heat waves should be done within a more global framework adopted after a systematic analysis of vulnerability (Füssel, 2007; Vescovi et al., 2005).

ACKNOWLEDGMENTS

Ricardo Trigo and Ricardo García-Herrera received support from the Portuguese-Spanish integrated action (E-27/2005) funded by CRUP and MCYT and also from Gulbenkian Foundation through project IMPACTE (no. 1568). Erich Fischer was funded by the Swiss National Centre of Competence in Research on Climate (NCCR Climate). The authors would like to thank the ECMWF and NCEP/NCAR for providing their reanalysis data, and the Belgium institute VITO for providing the images from satellite VEGETATION. The authors would like to acknowledge Daniel Paredes, David Barriopedro, Bernardo Mota, José Miguel Cardoso Pereira, Célia Gouveia, and Martin Hirschi for all their comments and contribution to several figures. We also acknowledge the comments and suggests from the reviewers.

REFERENCES

Albuisson, M., Delamare, C., Leroy, S., and Wald, L. (2003). Heatwave of summer 2003 enhanced by cloudless skies. Ecole des Mines de Paris, Paris, France.

Alcamo, J., Moreno, J. M., Nováky, B., Bindi, M., Corobov, R., Devoy, R. J. N., Giannakopoulos, C., Martin, E., Olesen, J. E., and Shvidenko, A. (2007). Europe. In Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and Hanson, C. E. (eds.). *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press, pp. 541–580.

André, J.C., Déqué, M., Rogel, P., and Planton, S. (2004). La vague de chaleur de l'été 2003 et sa prevision saisonière. *C.R. Geoscience*, 336, 491–503.

Barriopedro, D., García-Herrera, R., Lupo, A., and Hernández, E. (2006). A climatology of northern hemisphere blocking. *J. Clim.,* 19, 1042–1063.

Basu, R., and Samet, J.M. (2002). Relation between elevated ambient temperature and mortality: A review of the epidemiological evidence. *Epidemiol. Rev.,* 24, 190–202.

Beniston, M. (2004). The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. *Geophys. Res. Lett.,* 31, L02202.

Beniston, M., and Díaz, H. (2004). The 2003 heat wave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland. *Global Planet Change,* 44, 73–81.

Black, E., Blackburn, M., Harrison, G., Hoskins, B., and Methven, J. (2004). Factors contributing to the summer 2003 European heat wave. *Weather,* 59, 217–223.

Black, E., and Sutton, R. (2006). The influence of oceanic conditions on the hot European summer of 2003. *Clim. Dyn.,* 28, 53–66.

Botelho, J., Catarino, J., Carreira, M., Nogueira, P.J., Caldo, R., Paixao, E.J., et al., (2004). Onda de Calor de 2003: O seus efeitos sobre a mortalidade de populacao portuguesa. Direccao Geral de Saude, Lisboa, Abril.

Bouchama, A. (2004). The 2003 European heat wave. *Intensive Care Med.,* 30, 1–3.

Büntgen, U., Esper J., Frank, D. C., and Nievergelt, D. (2006). Alpine summer temperature variations, AD 755–2004. *J Clim.,* 19, 5606–5623.

Burt, S. (2004). The August 2003 heat wave in the United Kingdom, part 1: Maximum temperatures and historical precedents. *Weather*, 59, 199–208.

Carril, A.F., Gualdi, S., Cherchi, A., and Navarra, A. (2008). Heat waves in Europe: Areas of homogeneous variability and links with the regional to large-scale atmospheric and SSTs anomalies. *Clim. Dyn*., 30, 77–98.

Cassadou, S., Le Tertre, A., Medina, S., et al., (2004). Excess deaths during the 2003 heat wave in France: Which contribution of air pollution? *Epidemiology,* 15, S125.

Cassou, C., and Terray, L. (2005). Tropical Atlantic influence on European heat waves. *J. Clim.,* 18, 2805–2811.

Chase, T.N., Wolter, K., Pielke, R.A., and Rassol, I. (2006). Was the 2003 European summer heat wave unusual in a global context? *Geophys. Res. Lett*., 33, L23709.

Chuine, I., Yiou, P., Viovy, N., Seguin, B., Daux, V., and Le Roy Ladurie, E. (2004). Grape ripening as a past climate indicator. *Nature,* 432, 289–290.

Ciais, P., et al., (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature,* 437, 529–533.

Cohen, J.C., Bessemoulin, P., Courtier, P., and Veysseire, J.M. (2004). Bioclimatological aspects of summer 2003 over France. Meeting of experts to develop Guidelines on Heat-Health Warning Systems. Freiburg, 14–16 April.

Conti, S., Meli, P., Minelli, G., Solimini, R., Toccaceli, V., et al., (2005). Epidemiologic study of mortality during the summer 2003 heat wave in Italy. *Environ. Res.,* 98, 390–399.

COPA COGECA. (2003). Assessment of the impact of the heat wave and drought of the summer 2003 on agriculture and forestry. Fact sheets of the Committee of Agricultural Organisations in the European Union and the General Committee for Agricultural Cooperation in the European Union. Available at: http://www.copa-cogeca.com/pdf/pocc_03_78i4_1e.pdf (accessed).

Della-Marta, P.M., Haylock, M.R., Luterbacher, J., and Wanner, H. (2007a). The length of western European summer heatwaves has doubled since 1880. *J. Geophys. Res.,* 112, D15103.

Della-Marta, P.M., Luterbacher, J., von Weissenfluh, H., Xoplaki, E., Brunet, M., and Wanner, H. (2007b). Summer heat waves over western Europe 1880–2003, their change and relationship to large scale forcings. *Clim. Dyn.,* 29, 251– 275.

Dhainaut, J.F., Claessens, Y.E., Ginsburg, C., and Riou, B. (2004). Unprecedented heat-related deaths during the 2003 heat wave in Paris: Consequences on emergency departments. *Crit. Care,* 8, 1–2.

Díaz, J., García, R., Ribera, P., Alberdi, J.C., Hernández, E., Pajares, M.S., and Otero, A. (1999). Modeling of air pollution and its relationship with mortality and morbidity in Madrid, Spain. *Int. Arch. Occup. Environ. Health,* 72, 366–376.

Díaz, J., García, R., Velázquez de Castro, F., Hernández, E., López, C., and Otero, A. (2002a). Effects of extremely hot days on people older than 65 years in Seville (Spain) from 1986 to 1997. *Int. J. Biometerol.,* 46, 145–149.

Díaz, J., García-Herrera, R., Trigo, R.M., Linares, C., Valente, M.A., De Miguel, J.M., and Hernández, E. (2006a). The impact of summer 2003 heat wave in Iberia: How should we measure it? *Int. J. Biometeorol.,* 50, 159–166.

Díaz, J., Linares, C., López, C., García-Herrera, R., and Trigo, R.M. (2004). Impact of temperature and air pollution on child mortality in Madrid. *J. Occup. Environ. Med.,* 46, 768–774.

Díaz, J., Linares, C., and Tobías, A. (2006b). Impact of extreme temperatures on daily mortality in Madrid (Spain) among the 45–64 age-group. *Int. J. Biometeorol.,* 50, 342–348.

Díaz, J., López, C., Alberdi, J.C., Jordán, A., García, R., Hernández, E., and Otero, A. (2002b). Heat waves in Madrid 1986–1997: Effects on the health of the elderly. *Int. Arch. Occup. Environ. Health,* 75, 163–170.

Emberson, L.D., Simpson, D., Tuovinen, J.-P., Ashmore, M.R., and Cambridge, H.M. (2000). Towards a model of ozone deposition and stomatal uptake over Europe. EMEP/MSC-W Note 6/00.

European Commission, San-Miguel-Ayanz, J., Barbosa, P., Camia, A., Kucera, J., Libertà, G., Schmuck, G., Schulte, E., Bucella, P., Colletti, L., and Flies, R. (2004).

Forest fires in Europe: 2003 fire campaign. Official Publication of the European Communities, SPI.04.124 EN.

Ferranti, L., and Viterbo, P. (2006). The European summer of 2003: Sensitivity to soil water initial conditions. *J. Clim.,* 19, 3659–3680.

Feudale, L., and Shukla, J. (2007). Role of Mediterranean SST in enhancing the European heat wave of summer 2003. *Geophys. Res. Lett.,* 34, L03811.

Fiala, J., Cernikovsky, L., de Leeuw, F., and Kurfuerst, P. (2003). Air pollution by ozone in Europe in summer 2003. Overview of exceedances of EC ozone threshold values during the summer season April–August 2003 and comparisons with previous years. Copenhagen, European Environment Agency. EEA Topic Report 3/2003.

Fink, A.H., Brücher, T., Krüger, A., Leckebusch, G.C., Pinto, J.G., and Ulbrich, U. (2004). The 2003 European summer heatwaves and drought—synoptic diagnosis and impacts. *Weather,* 59, 209–216.

Fischer, E.M., Seneviratne, S. I., Lüthi, D., and Schär, C. (2007a). Contribution of land-atmosphere coupling to recent European heatwaves. *Geophys. Res. Lett.,* 34, L06707.

Fischer, E. M., Seneviratne, S. I., Vidale, P. L., Lüthi, D., and Schär, C. (2007b). Soil moisture—atmosphere interactions during the 2003 European summer heatwave. *J. Clim.,* 20, 5081–5099.

Fischer, P.H., Brunekreef, B., and Lebret, E. (2004). Air pollution related deaths during the 2003 heat wave in the Netherlands. *Atmos. Environ.,* 38, 1083–1085.

Fouillet, A., Rey, G., Laurent, F., et al., (2006). Excess mortality related to the August 2003 heat wave in France. *Int. Arch. Occup. Environ. Health,* 80, 16–24.

Füssel, H. M. (2007). Vulnerability: A generally applicable conceptual framework for climate change research. *Global Environ. Change,* 17, 155–167.

García-Herrera, R., Díaz, J., Trigo, R.M., and Hernández, E. (2005). Extreme summer temperatures in Iberia: Health impacts and associated synoptic conditions. *Ann. Geophys.,* 23, 239–251.

Garssen, J., Harmsen, C., and de Beer, J. (2005). The effect of the summer 2003 heat wave on mortality in The Netherlands. Available at: http://www.eurosurveillance.org/em/v10n07/1007-227.asp (accessed).

Gehrig, R. (2006). The influence of the hot and dry summer 2003 on the pollen season in Switzerland. *Aerobiologia,* 22, 27–34.

Gobron, N., Pinty, B., Mélin, F., Taberner, M., Verstraete, M.M., Belward, A., Lavergne, T., and Widlowski, J.-L. (2005). The state of vegetation in Europe following the 2003 drought. *Int. J. Remote Sens.*, 26, 2013–2020.

Grazzini, F., and Viterbo, P. (2003). Record breaking warm sea surface temperature of the Mediterranean Sea. *ECMWF Newsletter,* 98, 30–31.

Grize, L., Huss, A., Thommen, O., Schindler, C., and Braun-Fahrlander, C. (2005). Heat wave 2003 and mortality in Switzerland. *Swiss Med. Wkly.,* 135, 200–205.

Gruber, S., Hoelzle, M., and Haeberli, W. (2004). Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003. *Geophys. Res. Lett.,* 31, L13504.

Häberli, W., Paul, F., Gruber, S., Frauenfelder, R., Hoelzle, M., Kääb, A., Machguth, H., Noetzli, J., Rothenbühler, C., Vonder Mühll, D., and Zemp, M. (2005). Effects of the extreme summer 2003 on glaciers and permafrost in the Alps. Geograph. Inst., Universität Zürich, Zürich, Switzerland.

Hansen, J., Ruedy, R., Sato, M., Imhoff, M., Lawrence, W., Easterling, D., Peterson, T., and Karl, T. (2001). A closer look at United States and global surface temperature change. *J. Geophys. Res.*, 106, 23,947–23,963.

Hirschi, M., Seneviratne, S. I., and Schär, C. (2006a). Seasonal variations in terrestrial water storage for major mid-latitude river basins. *J. Hydrometeorol.,* 7, 39–60.

Hirschi, M., Viterbo, P., and Seneviratne, S. I. (2006b). Basin-scale water-balance estimates of terrestrial water storage variations from ECMWF operational forecast analysis data. *Geophys. Res. Lett.,* 33, L21401.

Hodzic, A., Madronich, S., Bohn, B., Massie, S., Menut, L., and Wiedinmyer, C. (2007). Wildfire particulate matter in Europe during summer 2003: Meso-scale modeling of smoke emissions, transport and radiative effects. *Atmos. Chem. Phys.,* 7, 4043–4064.

Hodzic, A., Vautard, R., Chepfer, H., Goloub, P., Menut, L., Chazette, P., Deuzée, J. L., Apituley, A., and Couvert, P. (2006). Evolution of aerosol optical thickness over Europe during the August 2003 heat wave as seen from CHIMERE model simulations and POLDER data. *Atmos. Chem. Phys.,* 6, 1853–1864.

Holstein, J., Canoui-Poitrine, F., Neumann, A., Lepage, E., and Spira, A. (2005). Were less disabled patients the most affected by 2003 heat wave in nursing homes in Paris, France? *J. Public Health.,* 27, 359–365.

Instituto Nazionale di Statistica (ISTAT). (2004). Bilancio demografico nazionale. Anno 2003. Available at: http://www.istat.it/salastampa/comunicati/ (accessed).

Jaffe, D., Bertschi, I., Jaegle, L., Novelli, P., Reid, J. S., Tanimotot, H., Vingarzan, R., and Westphal, D. L. (2004). Long-range transport of Siberian biomass burning emissions and impact on surface ozone in western North America. *Geophys. Res. Lett.,* 31, L16106.

Jankowski, T., Livingstone, D.M., Buhrer, H., Forster, R., and Niederhauser, P. (2006). Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world. *Limnol. Oceanogr.,* 51, 815–819.

Johnson, H., Cook, L., and Rooney, C. (2004). Mortality during the heat wave of August 2003 in England and Wales and the use of rapid weekly estimates. WHOFIC/04.081.

Johnson, H., Kovats, R.S., McGregor, G., Stedman, J., Gibbs, M., and Walton, H. (2005). The impact of the 2003 heat wave on mortality and hospital admissions in England. *Health Stat. Q.,* 25, 6–11.

Jolly, W.M., Dobbertin, M., Zimmermann, N. E., and Reichstein, M. (2005). Divergent vegetarion growth responses to the 2003 heat wave in the Swiss Alps. *Geophys. Res. Lett.,* 32, L18409.

Jung, T., Ferranti, L., and Tompkins, A. M. (2006). Response to the summer 2003 Mediterranean SST anomalies over Europe and Africa. *J. Clim.*, 19, 5439–5454.

Kalkstein, L.S. (1995). Lessons from a very hot summer. *Lancet,* 346, 857–859.

Keenan, D.J. (2007). Grape harvest dates are poor indicators of summer warmth. *Theor. Appl. Climatol.,* 87, 255–256.

Keller, F., and Fuhrer, J. (1995). Die Landwirtschaft und der Hitzesommer 2003. *Umwelt Forschung,* 11, 403–411.

Kistler, R., et al., (2001). The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation. *Bull. Am. Meteorol. Soc.,* 82, 247–267.

Klinenberg, E. (2003). *Heat wave: A social autopsy of disaster in Chicago*. Chicago: University of Chicago Press.

Kosatsky, T. (2005). The 2003 European heat waves. *Eurosurveill.*, July 1, 10(7), article 2.

Kovats, R.S., Hajat, S., and Wilkinson, P. (2004a). Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK. *Occup. Environ. Med.*, 61, 893–898.

Kovats, R.S., Wolf, T., and Menne B. (2004b). Heat wave of August 2003 in Europe: Provisional estimates of the impact on mortality. *Eurosurveillance Weekly*, March 11, 8(11).

Lagadec, P. (2004). Understanding the French 2003 heat wave experience: Beyond the heat, a multi-layered challenge. *J. Conting. Crisis. Manag.,* 12, 160–169.

Le Roy Ladurie, E., Daux, V., and Luterbacher, J. (2006). Le climat de Bourgogne et d'ailleurs XIVe-XXe siècle. *Hist. Econo. Soc. (HES),* 3, 421–436.

Le Tertre A, et al., (2006). Impact of the 2003 heatwave on all-cause mortality in nine French cities. *Epidemiology,* 17, 75–79.

Levison, D.H., and Waple, A.M. (2004). State of the climate in 2003. *Bull. Am. Meteorol. Soc.,* 85, S1–S72.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., and Wanner, H. (2004). European seasonal and annual temperature variability, tends and extremes since 1500. *Science,* 303, 1499–1503.

Luterbacher, J., Liniger, M.A., Menzel, A., Estrella, N., Della-Marta, P.M., Pfister, C., Rutishauser, T., and Xoplaki, E. (2007). The exceptional European warmth of Autumn 2006 and Winter 2007: Historical context, the underlying dynamics and its phenological impacts. *Geophys. Res. Lett.,* 34, L12704.

Martínez, F., Simón-Soria, F., and López-Abente, G. (2004). Valoración del impacto de la ola de calor del verano de 2003 sobre la mortalidad. *Gac. Sanit.,* 18, 250–258.

Meehl, G.A., and Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science,* 305, 994–997.

Meier, N., Rutishauser, T., Pfister, C., Wanner, H., and Luterbacher, J. (2007). Grape harvest dates as a proxy for Swiss April to August temperature reconstructions back to AD 1480. *Geophys. Res. Lett.,* 34, L20705.

Menzel, A. (2005). A 500-year pheno-climatological view on the 2003 heatwave in Europe assessed by grape harvest dates. *Meteorol. Zeitschrift.,* 14, 75–77.

Michelozzi, P., de Donato, F., Bisanti, L., Russo, A., et al., (2005). The impact of the summer 2003 heat wave on mortality in four Italian cities. *Eurosurveill.,* 10 (7/8).

Misset, B., De Jonghe, B., Bastuji-Garin, S., et al., (2006). Mortality of patients with heatstroke admitted to intensive care units during the 2003 heat wave in France: A national multiple-center risk-factor study. *Crit. Care Med.,* 34, 1087–1092.

Mitchell, T., and Jones, P. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol.,* 25, 693–712.

Mouthon, J., and Daufresne, M. (2006). Effects of the 2003 heatwave and climatic warming on mollusc communities of the Saone: A large lowland river and of its two main tributaries (France). *Global Change Biol.,* 12, 441–449.

Munich Re. (2004). *TOPICS geo 2003*. Munich: Münchener Rückverischerungs-Gessellschaft.

Nogueira, P.J., and Paixão, E.J. (2008). Models for mortality associated with heat waves: Update of the Portuguese heat health warning system. *Int J Climatol.,* 28(4), 545–562.

Ogg, J. (2005). Heatwave: Implications of the 2003 French heat wave for the social care of older people. Young Foundation working paper 2.

Ogi, M., Yamazaki, K., and Tachibana, Z. (2005). The summer northern annular mode and abnormal summer weather in 2003. *Geophys. Res. Lett.,* 32, L04706.

Ordoñez, C., Mathis, H., Furger, M., Henne, S., Huglin, C., Staehelin, J., and Prevot, A. S. H. (2005). Changes of daily surface ozone maxima in Switzerland in all seasons from 1992 to 2002 and discussion of summer 2003. *Atmos. Chem. Phys.,* 5, 1187–1203.

Orsolini, Y. J., and Nikulin, G. (2006). A low-ozone episode during the European heat wave of August 2003. *Q. J. Roy. Met. Soc.,* 132, 667–680.

Pascal, M., Laaidi, K., Ledrans, M., et al., (2006). France's heat health watch warning system. *Int. J. Biometeorol.,* 50, 144–153.

Pellerin, D., and Hamard, H. (2003). The medical care of elderly. The lessons of the heat wave. *Bull. Acad. Nat. Med.,* 187, 1417–1421.

Pereira, J.M.C., and Santos, T.N. (2003). *Fire risk and burned area mapping in Portugal*. Lisboa: Direcção-Geral das Florestas.

Pereira, M.G., Trigo, R.M., da Camara, C.C., Pereira, J.M.C., and Leite S.M. (2005). Synoptic patterns associated with large summer forest fires in Portugal. *Agri. For. Meteorol.,* 129, 11–25.

Poumadere, M., Mays, C., and Le Mer, S. (2005). The 2003 heat wave in France: Dangerous climate change here and now. *Risk Anal.*, 25, 1483–1494.

Rebetez, M. (2004). Summer 2003 maximum and daily temperatures over a 3300 m altitudinal range in the Alps. *Clim. Res.,* 27, 45–50.

Rex, D. F. (1950). Blocking action in the middle troposphere and its effect upon regional climate, part I: An aerological study of blocking action. *Tellus,* 2, 196–211.

Rouault, G., Candau, J.N., Lieutier, F., Nageleisen, L.M., Martin, J.C., and Warzée, N. (2006). Effects of drought and heat on forest insect populations in relation to the 2003 drought in Western Europe. *Ann. For. Sci.,* 63, 613–624.

Rudolf, B., Beck, C., Grieser, J., and Schneider, U. (2007). *Global precipitation analysis products*. Offenbach, Germany: Global Precip. Climatol. Cent., Dtsch. Wetterdienst,.

Sartor, F. (2004). *La surmortalité en Belgique au cours de l'été 2003*. Section d'épidémiologie, juin 2004. Bruxelles: Institut Scientifique de Santé Publique, IPH/EPI Reports n° 2004 – 009, D/2004/2505/17.

Schär, C., and Jendritzky, G. (2004). Hot news from summer 2003. *Nature,* 432, 559–560.

Schär, C., Vidale, P.L., Lüthi, D., Frei, C., Häberli, C., Liniger, M.A., and Appenzeller C. (2004). The role of increasing temperature variability in European summer heat waves. *Nature,* 427, 332–336.

Schönwiese, C.D., Staeger, T., and Trömel, S. (2004). The hot summer 2003 in Germany. Some preliminary results of a statistical time series analysis. *Meteorol. Zeitschrift.,* 13, 323–327.

Shabalova, M.V., and van Engelen, A.F.V. (2003). Evaluation of a reconstruction of winter and summer temperatures in the Low Countries, AD 764–1998. *Clim. Change,* 58, 219–242.

Solberg, S., Coddeville, P., Forster, C., Hov, Ø., Orsolini, Y., and Uhse, K. (2005). European surface ozone in the extreme summer 2003. *Atmos. Chem. Phys. Discuss.,* 5, 9003–9038.

Solberg, S., Hov, Ø., Søvde, A., Isaksen, I. S. A., Coddeville, P., De Backer, H., Forster, C., Orsolini, Y., and Uhse, K. (2008). European surface ozone in the extreme summer 2003. *J. Geophys. Res.,* 113, D07307.

Stott, P. A., Stone, D. A., and Allen, M. R. (2004). Human contribution to the European heatwave of 2003. *Nature,* 432, 610–613.

Thommen Dombois, O., and Braun-Fahrländer, C. (2004). Gesundheitliche Auswirkungen der Klimaänderung mit Relevanz für die Schweiz. Literaturstudie im Auftrag des Bundesamtes für Umwelt, Wald und Landschaft (BUWAL) und des Bundesamtes für Gesundheit (BAG).

Tressol, M., Ordoñez, C., Zbinden, R., Brioude, J., Thouret, V., Mari, C., Nedelec, P., Cammas, J.-P., Smit, H., Patz, H.-W., and Volz-Thomas, A. (2008). Air pollution during the 2003 European heat wave as seen by MOZAIC airliners. *Atmos. Chem. Phys.,* 8, 2133–2150.

Trigo, R.M., García-Herrera, R., Díaz, J., Trigo, I.F., and Valente, A. (2005). How exceptional was the early August 2003 heatwave in France? *Geophys. Res. Lett.,* 32, L10701.

Trigo, R.M., Pereira, J.M.C., Pereira, M.G., Mota, B., Calado, M.T., DaCamara, C.C., and Santo, F.E. (2006). The exceptional fire season of summer 2003 in Portugal. *Int. J. Climatol.,* 26, 1741–1757.

Trigo, R.M., Trigo, I.M., DaCamara, C.C., and Osborn, T.J. (2004). Winter blocking episodes in the European-Atlantic sector: Climate impacts and associated physical mechanisms in the reanalysis. *Clim. Dyn.,* 23, 17–28.

UNEP. (2004). The European summer heat wave of 2003. UNEP Brief. United Nations Environmental Programme, Nairobi, Kenya.

Valleron, A.J., and Boumendil, A. (2004). Epidemiology and heat waves: Analysis of the 2003 episode in France. *C.R. Biologies,* 327, 1125–1141.

Vandentorren, S., Bretin, P., Zeghnoun, A., Mandereau-Bruno, L., Croisier, A., Cochet, C., Ribéron, J., Siberan, I., Declercq, B., and Ledrans, M. (2006). August 2003 heat wave in France: Risk factors for death of elderly people living at home. *Eur. J. Public Health,* 16, 583–591.

Vandetorren, S., Suzan, F., Medina, S., Pascal, M., Maulpoix, A., Cohen, J.C., and Ledrans M. (2004). Mortality in 13 French cities during the August 2003 heat wave. *Am. J. Public Health,* 94, 1518–1520.

Vautard, R., Beekmann, M., Desplat, J., Hodzic, A., and Morel, S. (2007). Air quality in Europe during the summer of 2003 as a prototype of air quality in a warmer climate. *C.R. Geosciences,* 339, 747–763.

Vautard, R., Honore, C., Beekmann, M., and Rouil, L. (2005). Simulation of ozone during the August 2003 heat wave and emission control scenarios. *Atmos. Environ.,* 39, 2957–2967.

Vescovi, L., Rebetez, M., and Rong, F. (2005). Assessing public health risk due to extremely high temperatures events: Climate and social parameters. *Clim. Res.,* 30, 71–78.

WHO. (2004). Heat waves: Risks and responses. Health and Global Environmental Change. Series No. 2.

Xoplaki, E., Luterbacher, J., and González-Rouco, J.F. (2006). Mediterranean summer temperature and winter precipitation, large-scale dynamics, trends. *Il Nuovo Cimento*, 29, 45–54.

Xoplaki, E., Luterbacher, J., Paeth, H., Dietrich, D., Steiner, N., Grosjean, M., and Wanner, H. (2005). European spring and autumn temperature variability and change of extremes over the last half millennium. *Geophys. Res. Lett.,* 32, L15713.

Yurganov, L. N., Duchatelet, P., Dzhola, A. V., Edwards, D. P., Hase, F., Kramer, I., Mahieu, E., Mellqvist, J., Notholt, J., Novelli, P. C., Rockmann, A., Scheel, H. E., Schneider, M., Schulz, A., Strandberg, A., Sussmann, R., Tanimoto, H., Velazco, V., Drummond, J. R., and Gille, J. C. (2005). Increased Northern Hemispheric carbon monoxide burden in the troposphere in 2002 and 2003 detected from the ground and from space. *Atmos. Chem. Phys.,* 5, 563–573.