The 2003 European summer heatwaves and drought – synoptic diagnosis and impacts

Andreas H. Fink
Tim Brücher
Andreas Krüger
Gregor C. Leckebusch
Joaquim G. Pinto
Uwe Ulbrich

Institute of Geophysics and Meteorology, University of Cologne, Germany

Europe was affected by a series of strong, persistent heatwaves during the summer of 2003. The largest positive anomalies in monthly mean temperatures were observed in June and August in a region stretching from south-west Germany across Switzerland to the eastern and southern parts of France (Figs. 1(a) and (e)). In eastern France, the northern parts of Switzerland and the German Alpine foreland, the June–August 2003 period was more than 5 degC warmer than the 1961–90 average, making 2003 the warmest summer in the above-mentioned area since at least 1864 (Schär *et al.* 2004; Bader and Zbinden 2003), but more likely since instrumental records began in the mid-to-late eighteenth century (Fricke 2003; Schönwiese *et al.* 2004). As a result, the impacts and the media interest were extraordinary. The World Health Organization (WHO) has estimated that the extreme heat caused more than 15 000 excess deaths in France, Portugal, and Italy alone (WHO 2003). In the European Alps, extreme snow and glacier melt led to such an increased level of ice and rock falls in the mountain faces that the normal climbing routes to the highest and the most famous Alpine peaks (Mont Blanc and Matterhorn) had to be closed by the local authorities. Even though summer 2003 is not amongst the driest on record in central Europe, the impacts of its dryness (Figs. 1(b), (d), and (f)) were augmented by high evapotranspiration rates and drought conditions during the previous spring. As a consequence, large losses in crop yield and extremely low discharge levels of rivers were reported in large parts of Europe.

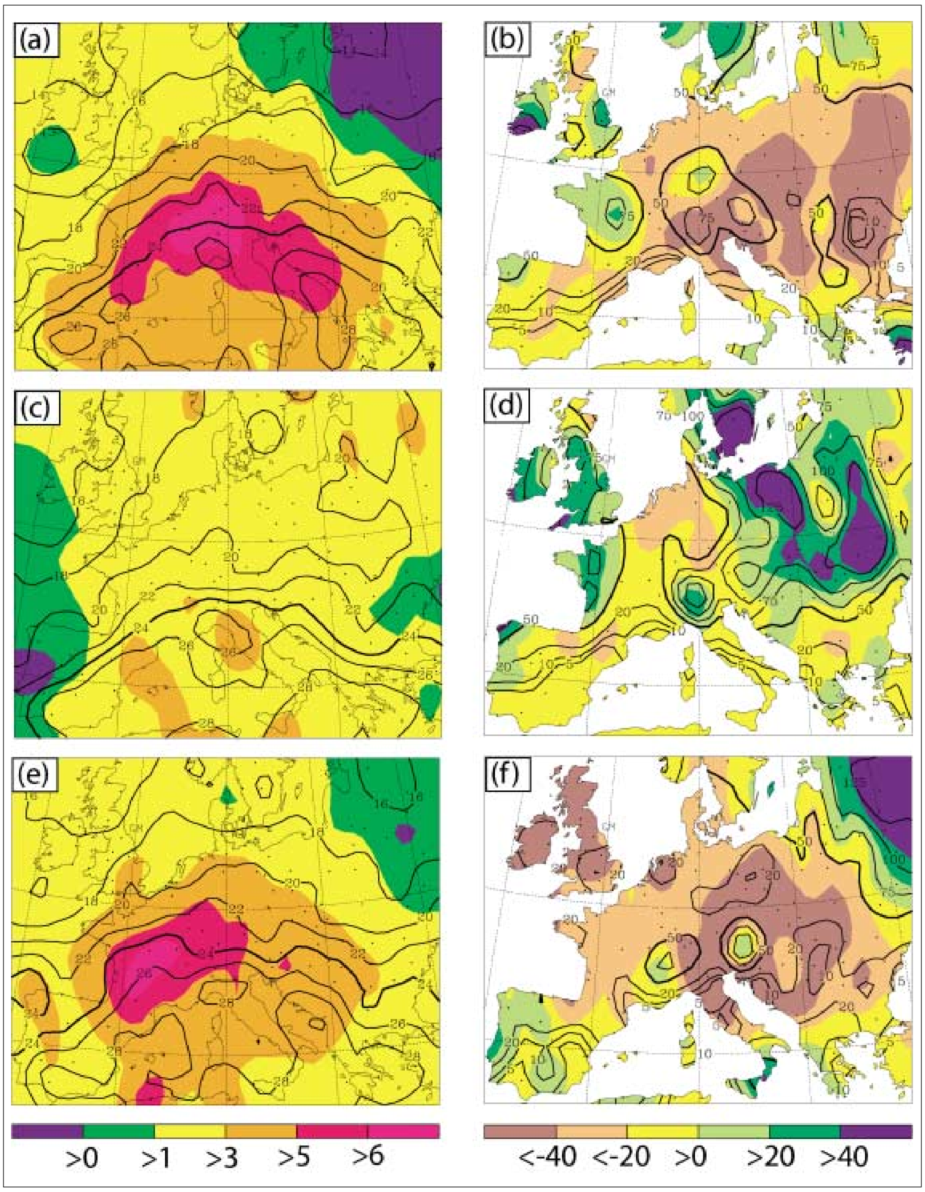

Fig. 1 Mean June (a), July (c), and August (e) 2003 temperatures (contours in increments of 2 degC, 24 °C isopleths in bold) and anomalies (degC, colours) with respect to the 1961–90 reference period. (b), (d), and (f), as (a), (c), and (e) but for accumulated monthly precipitation. Contours drawn are the 5, 10, 20, 50, 100, and 125 mm isopleths. (Data source: CLIMAT reports of monthly values issued by the national weather services. All stations with an altitude below 800 m were used. Black dots and crosses indicate locations of stations used (crosses indicate stations where anomalies could not be computed due to lacking climate values).)

In the present article, we will first give some details about the heat and drought conditions and put the observed extreme values into the historical context of instrumental observations. Next, we will discuss how far the unusual heatwaves, especially the most extreme one occurring in the first fortnight of August, can be explained by the anomalous occurrence and persistence of anticyclonic weather types over central Europe. After briefly discussing the impacts of the warmth and dryness on agricultural production, the European power market, and Alpine glaciers, we will discuss potential future trends in extreme summer weather in Europe.

Summer 2003 in temperature, sunshine, and precipitation records

Figure 1 displays interpolated station values of monthly mean temperature and precipitation, in combination with their anomalies with respect to the 1961–90 reference period for June, July, and August 2003. From the temperature maps (Figs. 1(a), (c), and (e)) it is clearly evident that June and August were the warmest months, even though July was also warmer than average by about 1–3 degC (Fig. 1(c)). In June, several lowland and mountain stations reported monthly anomalies in excess of 7 degC. Examples are Geneva in Switzerland (+7.6 degC) and the Feldberg mountain top (altitude 1493 m) in the Black Forest (+7.1 degC). In August 2003, the deviation from the monthly mean was more than +6 degC at many stations in south-west Germany, Switzerland, and France (*e.g.* the above-mentioned Feldberg, and Bourges in central France, both +6.6 degC). In contrast to June, when the warm anomalies lasted throughout the entire month, August was characterised by an extreme heatwave from 1 to 13 August during which many all-time temperature records tumbled in much of Europe. For example, the old Swiss temperature record of 39.0 °C observed on 2 July 1952 in Basel was greatly exceeded by the 41.5 °C reading in Grono (Mesolcina valley in the Canton Grisons, south Alps) on 11 August 2003 (Bader and Zgraggen 2003). In Germany, daily maximum temperatures exceeding 40 °C were recorded three times: on 9 August 40.2 °C was measured at Karlsruhe and on the 13th again at Freiburg and Karlsruhe, exactly equalling the previous record observed on 27 July 1983 at Gärmersdorf (Bavaria). In central and eastern France, the daily maximum temperatures soared above 40 °C at individual synoptic weather stations every day between 5 and 13 August, culminating in 41.1 °C at Auxerre (Burgundy) on 6 August and 40.9 °C at Colmar (Alsace, in the upper Rhine valley) on 13 August. In addition, the night-time minimum temperatures remained extremely high. The 27.6 °C observed on 13 August at Weinbiet, located on the western slopes of the middle Rhine valley, is the highest minimum temperature ever recorded in Germany (previous record 26.5 °C at Freiburg on 5 July 1957). As noted above, the summer dryness was not record-breaking. However, the hottest months, June and August, were accompanied by strong negative precipitation anomalies (Figs. 1(b) and (f)), whereas July was only slightly drier than normal in large parts of west central Europe (Fig. 1(d)). The positive precipitation anomalies over the western Alps in July in Fig. 1(d) are related to above average rainfall in southern Switzerland, but the regions north of the Alpine main divide were mostly slightly drier than normal.

The extraordinary nature of summer 2003 can be assessed from the long temperature record at Basel-Binningen dating back to 1755. Although some caution with respect to homogeneity of the time-series before 1864 must be taken into account (Bader and Zbinden 2003), the mean June–August 2003 temperature of 22.8 °C is an outlier in the Basel series (Fig. 2(a)), thus making 2003 by far the warmest summer since observations started in 1755. This conclusion is corroborated by the discussion in Fricke (2003) of the long (since 1781) homogeneous time-series of Hohenpeissenberg, a 986 m mountain top located in the Bavarian Alpine foreland. Note that the summer of 1947, the second warmest in Basel, had a mean temperature of only 20.6 °C. The summer of 2003 was also the sunniest ever in Basel since observations began in 1886, with a sunshine duration of 907 hours (Fig. 2(a)), marginally exceeding the 902 hours of the second sunniest summer in 1911. A good impression of the development of the 2003 drought conditions with respect to the mean and other extreme years is provided in Fig. 2(b). It displays at a daily resolution the accumulated precipitation excess or deficit since the start of a calendar year with respect to the mean accumulation in the period 1879–2002 for Hohenpeissenberg. In the Bavarian Alpine

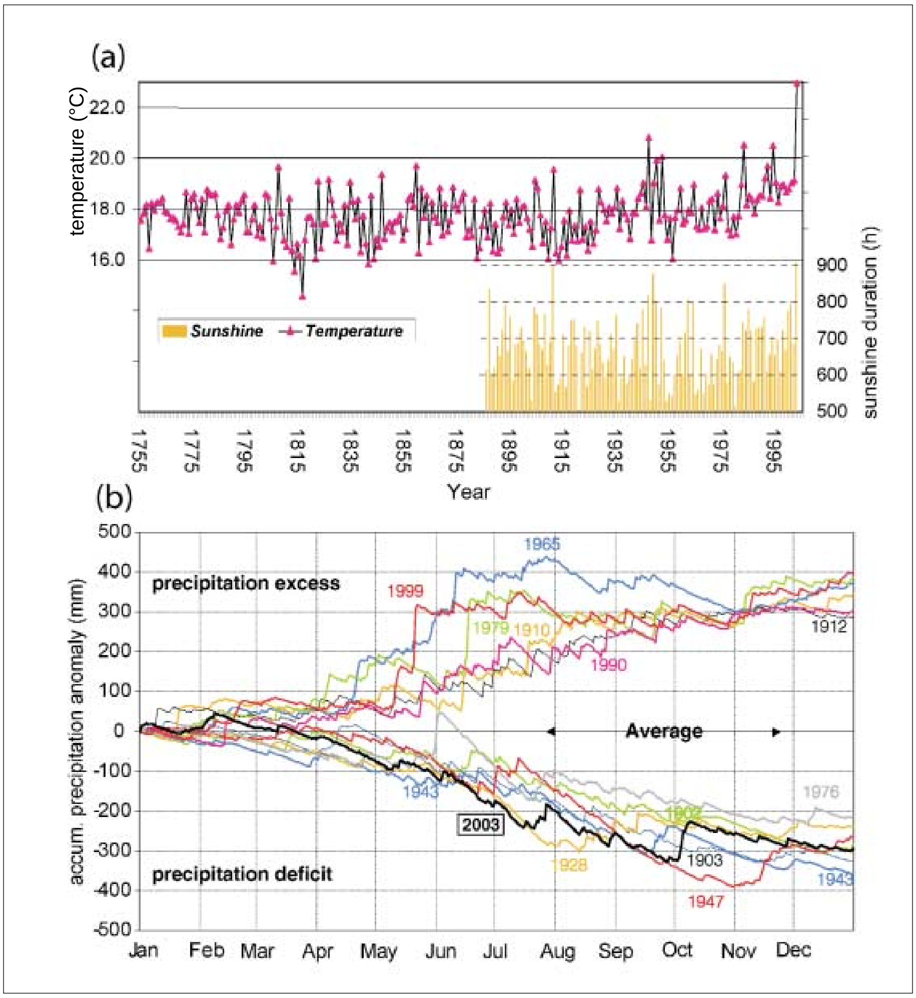

*Fig. 2 (a) Mean June–August temperature (curve, 1755–2003) and total sunshine duration (bars, 1886–2003) at the Swiss station Basel-Binnigen (altitude 316 m). (b) Annual development of accumulated daily precipitation anomalies (reference period: 1879–2002) of the six (seven) wettest (driest) years at Hohenpeissenberg (altitude 986 m) during the period 1879–2003 (*i.e.* the reference period plus the anomalous year of 2003). The station is located on a low mountain top in the Bavarian foreland of the Alps. ((b) is courtesy of Wolfgang Fricke, German Weather Service, Meteorological Observatory Hohenpeissenberg.)*

foreland, the drier than normal conditions developed in late March, and by mid-June the largest precipitation deficit on record was observed for this time of year. After some rainfall in the second half of July, the accumulated precipitation deficit again dropped to record low values in late August. Note that due to an anomalously wet October, 2003 only ended as the third driest on record. Figure 3 conveys an idea about the impact of the dryness on the river flow of a major central European river, the Rhine. It shows the minimum (1930–2002) daily discharge at Cologne, together with the corresponding hydrographs for 2003 and two other exceptionally dry years, 1947 and 1976 (cf. Fig. 2 (b)). The latter two years also belong to the six driest on record at Hohenpeissenberg (Fig. 2(b)). In the Rhine catchment the period with below average accumulated areal rainfall had commenced already in February (Belz *et al.* 2004). The same authors note that February, March, and August were the driest months in Germany's river catchments in 2003. In August, the lowest discharges at Cologne since 1930 were observed. However, the minimum September 2003 value of 640 m^{3}s^{-1} was considerably higher than the absolute minimum of 530 m^{3}s^{-1} in early November 1947. Two aspects are worthy of note. Firstly, the minimum water level at Cologne in late September 2003 was 81 cm, 3 cm lower than the 1947 value, thus representing the lowest gauge height on record. This emphasises the fact that discharge values are more meaningful than just water levels due to changes in the cross-section of the river bed. Secondly, the daily mean discharge of the River Elbe at Dresden in August–September 2003 was the second lowest on the observational record, just one year after the record-breaking Elbe flood in summer 2002 (see Ulbrich *et al.* 2003a).

Synoptic weather types (Grosswetterlagen) in 2003

In this section we try to answer the question as to what extent the prevalence of anticyclonic weather types is an explanatory factor of the observed warmth. To accomplish this goal, we use the subjective 'Grosswetterlagen' (GWL) statistics for central Europe which are available from 1881. The 30 GWL categories describe typical cyclonic, anticyclonic or neutral weather types over central Europe. They are subjectively determined for each calendar day on the basis of surface pressure and, since they are routinely available, also of 500 mbar geopotential height analyses. The statistics are published and updated by the German Weather Service. Examples of surface pressure and 500 mbar geopotential height charts for each GWL can be found on the website of the Potsdam Institute for Climate Impact Research (http://www.pik-potsdam.de/~uwerner/gwl/welcome.htm). In the period April–September 2003, the largest positive anomalies in the frequency of occurrence of anticyclonic weather types were associated with GWL 5 "Anticyclonic south-westerly regime", GWL 10 "Bridging of Azores and Russian highs over central Europe", and GWL 14 "High Norwegian Sea, anticyclonic surface conditions over central Europe". With respect to the reference period 1881–2002, the relative frequency of days with GWL 5, 10, and 14 between April and September 2003 was 9.3% (compared to the summer half-year average of 1.7%), 20.2% (7.2%), and 10.9% (4.2%), respectively. GWL 5 prevailed in the first half of June 2003. To give the reader an idea of the associated surface and mid-tropospheric conditions, the 500 mbar geopotential height and surface pressure distributions, computed from averaging the National Centers for Environmental Prediction four-times-daily reanalysis (Kalnay *et al.* 1996) between 5 and 11 June, are shown in Fig. 4(a). Corresponding to the definition of GWL 5, central Europe was dominated by an anticyclonic south-westerly flow regime with weak surface pressure gradients and a mid-level ridge aloft. Daily 5-day backward trajectories starting at 850 mbar over south-western Germany (not shown) indicate that this flow pattern was often associated with warm air advection from the western Mediterranean ahead of the trough north-west of the British Isles (Fig. 4 (a)). Between 22 July and 4 August, *i.e.* just before and at the beginning of the major heatwave, GWL 10 has been diagnosed over central Europe (Fig. 4 (b)). It was replaced by GWL 14, lasting from 5 until 13 August (Fig. 4 (c)).

Comparison of Figs. 4(b) and (c) clearly reveals that geopotential heights rose over central Europe during the latter period, and that the build-up of a surface high pressure zone stretching from the Azores to the Norwegian Sea completely inhibited the intrusion of low-level cooler air from the Atlantic and North Sea into central Europe. The peak of the summer heat occurred at the end of the above-noted period during which GWL 14 prevailed.

The question arises as to what extent the predominance of the anticyclonic GWLs 5, 10, and 14 can account for the 2003 summer heat. Figure 5 shows the 1890–2002 frequency distribution of mean daily temperatures at Karlsruhe (Germany) observed during days assigned to these GWLs for June, July and August. The colour-coded vertical lines in Fig. 5 denote the corresponding values observed during 2003. Whilst in June and July the 2003 mean daily temperatures are more or less within the hitherto observed range (Figs. 5(a) and (b)), the August 2003 result is striking; almost all daily mean temperatures occurring during GWL 14 (5–13 August) exceeded the maximum value observed since 1890 (Fig. 5(c)). Moreover, analyses of the Karlsruhe temperature data (not shown) revealed that there is no general build-up of heat during a succession of days with the same anticyclonic weather type. Thus, other factors that will be discussed in some more detail in the concluding section must have played the decisive role for the extreme heat in August. One reason discussed below, the desiccation of soils, is related to the dryness of the preceding spring season and the summer itself. Figure 6 illustrates the mean (1946–2002) and actual daily accumulated precipitation at Karlsruhe from January to December 2003. A simplified GWL statistic for 2003 that distinguishes between cyclonic weather types (blue), GWLs 5, 10, and 14 and all other anticyclonic weather types (light and dark orange) is also given in Fig. 6 by the colouring between the 2003

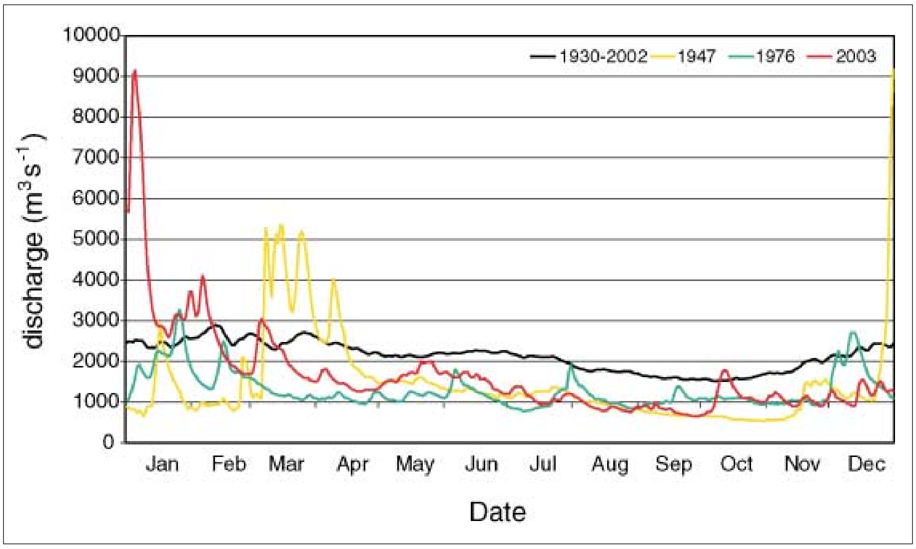

Fig. 3 Annual distribution of minimum daily discharge of the River Rhine at the water-level gauge at Cologne in a mean year (averaging period 1930–2002) and in the three extremely dry years of 1947, 1976, and 2003

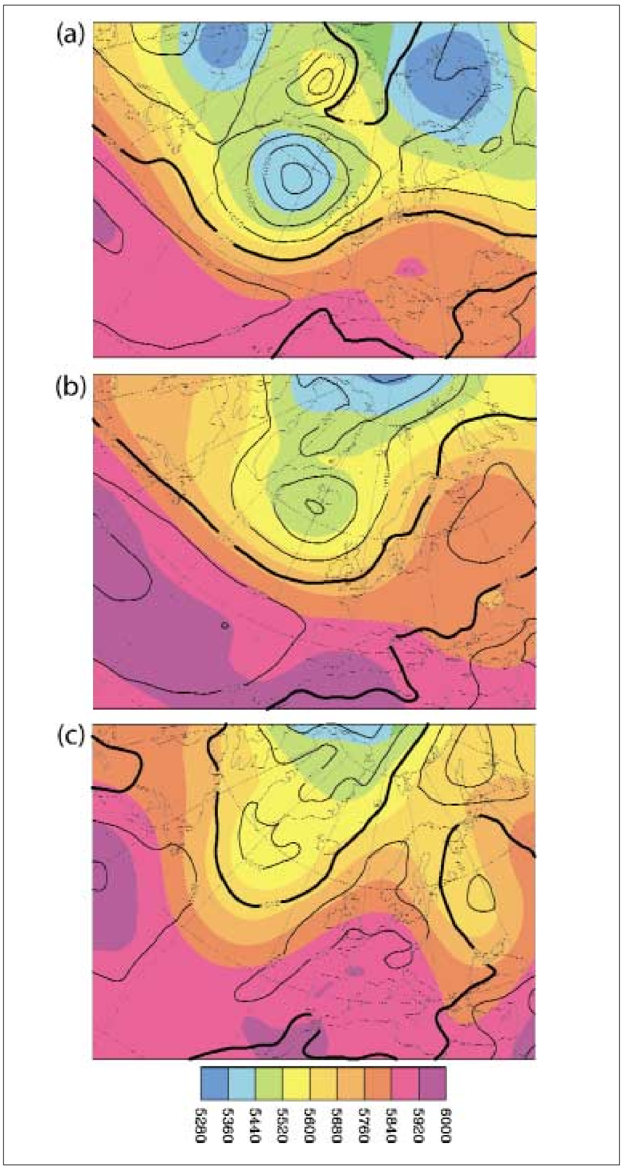

Fig. 4 Mean 500 mbar geopotential height (gpm, colours) and surface pressure charts (contours in increments of 5 mbar, 1015 mbar isopleths in bold) representing the anticyclonic GWLs (see text) that prevailed during the summer of 2003: (a) GWL 5, averaged between 5 and 11 June 2003, (b) GWL 10, 22 July–4 August, and (c) GWL 14, 5–13 August 2003

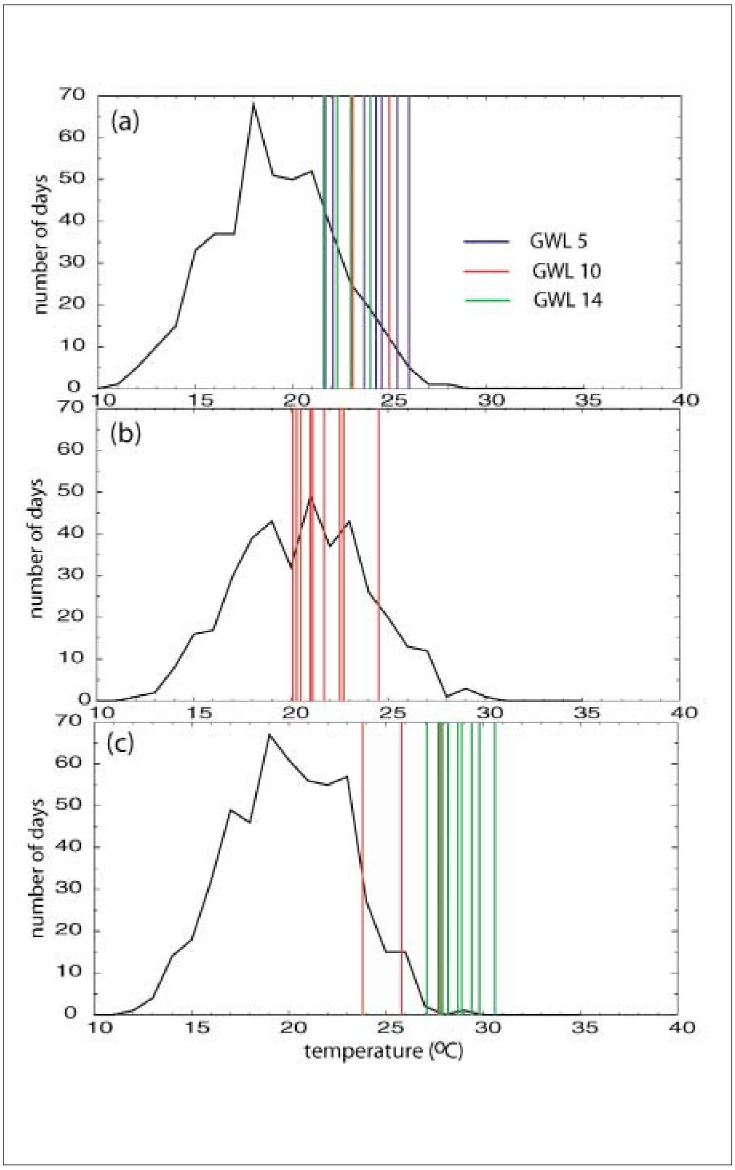

Fig. 5 Frequency of occurrence per 1 degC interval of daily mean June (a), July (b), and August (c) temperatures at the German station Karlsruhe (altitude 145 m) between 1890 and 2002. Only data from days which were assigned to anticyclonic GWLs 5, 10, and 14 (see text), respectively, are used. The vertical lines are drawn at the decimal values of the mean daily temperatures in 2003 for days that were assigned to GWL 5 (blue), 10 (red), and 14 (green) in 2003.

accumulated precipitation curve and the abscissa. The prevalence of anticyclonic weather types in 2003, especially in the first three quarters of the year is obvious. Also evident is the frequent occurrence of GWLs 5, 10, and 14 between June and September. The light and dark orange curves in the lower part of Fig. 6 show the development of the anomalous occurrence of GWLs 5, 10, and 14 and all other anticyclonic weather types in the course of 2003, respectively. The former anomaly rose to about 150% in August and September with respect to the 1946–2002 mean, *i.e.* days with GWLs 5, 10, and 14 have been observed by this time of the year 2.5 times as often since the beginning of the year as in a mean year. Note that all other anticylonic weather types were only slightly more frequent than normal. The gross development of negative rainfall anomalies in 2003 is in qualitative agreement with the dominance of anticyclonic weather in 2003. After a wetter than normal start to 2003, the accumulated precipitation curve intersected the mean in late March (Fig. 6). Subsequently, the rainfall deficit increased towards the summer and persisted until the end of the year. A similar behaviour has been noted above for Hohenpeissenberg (cf. Fig. 2(b)). Note from the actual curve of accumulated daily precipitation that sporadic (convective) rainfall events also occur during anticyclonic weather types, but the first 13 days of August stayed dry in Karlsruhe. Usually, extreme temperatures destabilise the atmosphere, enhancing the likelihood of afternoon thunderstorms that reduce the maximum temperatures on the day of their occurrence and, very often, also on the following day due to enhanced cloudiness and a moistened land surface. This process was not effectively acting in the first half of August 2003 due to the anomalous stabilising subsidence during this period (cf. Black *et al.*, this issue). Finally, note that anticyclonic GWLs occurred on each day of June 2003 (Fig. 6). Thus, the somewhat larger monthly temperature deviations, as compared to August 2003, are the result of the persistence of above average temperatures, but not of excessive temperature anomalies on individual GWL days in June 2003 (cf. Figs 5(a) and (c)).

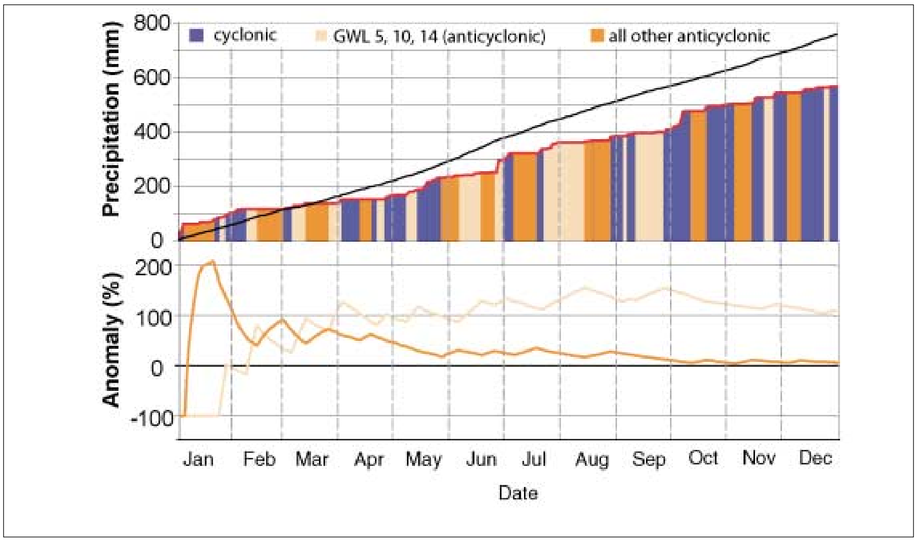

Fig. 6 Upper black and red curves: mean (1946–2002) and 2003 accumulated daily precipitation at Karlsruhe from January to December 2003. The shading below the red curve denotes the GWL (see text) assigned to each day of 2003. Coloured are all cyclonic (blue) and anticyclonic (dark orange) GWLs, except anticyclonic GWLs 5, 10, and 14 (light orange). Lower curves: anomalous frequencies of occurrence of anticyclonic GWLs 5, 10, and 14 (light orange) and all other anticyclonic GWLs (dark orange) accumulated since 1 January 2003.

Impacts

The drought and heatwaves in summer 2003 affected not only central Europe, but also the west central Mediterranean area (cf. Fig. 1). In this context, Grazzini and Viterbo (2003) note record-breaking high sea surface temperatures in this area peaking above 30 °C. While small-scale forest fires were observed all over central Europe and the western Mediterranean, the forest and bush fires on the Iberian peninsula were especially devastating. In Portugal, a total of 390 000 ha of forest and bush land were destroyed (the previous annual record loss of about 182 000 ha occurred in 1991) and 125 000 ha were burned in Spain. In much of Europe, the reduced crop yields, and shortages in green fodder supply to and increased mortality in the livestock and poultry stocks caused major financial losses to farmers. It is estimated that in France, Italy, Germany, Spain, Portugal, Austria, Hungary, Estonia, and Slovakia the financial losses due to agricultural and forestry damages add up to about 13.1 billion Euros (COPA-COGECA 2003). Another less perceived pan-European impact was felt on the power trade market. As discussed above, the flow of central European rivers approached all-time low levels in August and September 2003. Consequently, several power plants had to reduce their output because they could not divert enough cooling water either physically or legally from the rivers. For example, the German nuclear power facility Isar1 reduced its power generation by about 40%. Although no overall energy shortage arose (regional power outages and restrictions were reported from Italy in June), the prices for electricity increased. At the Amsterdam Power Exchange Spotmarket (APX) the average August 2003 base price increased to 83.98 Euros per MWh, while the previous year value was 40.87 Euros per MWh (APX 2003). The maximum daily base load price of 660.34 Euros per MWh was reached on 11 August 2003, as The Netherlands Transmission System Operator (Tennet), manager of the high-voltage grid, placed its cooling water restriction on red status due to water temperatures above 23 °C at the Rhine station Lobith on The Netherlands' eastern border. However, no shortages in drinking water supplies occurred in Germany due to a sufficient replenishment of groundwater resources and reservoirs in the anomalously wet October 2002 to January 2003 period.

As mentioned in the introduction, glaciers in the European Alps experienced an extreme ice melt and snowmelt. A good indicator of the annual ice and firn* gain/loss is the so-called specific mass balance in units of metres of water equivalent (m w.e.). It gives the net water depth – distributed across the area of the glacier – that melted or accumulated between the times of minimum snow-cover, usually in late September or early October. This roughly one-year period is called the 'glaciological year'. Mass balance measurements are extremely laborious and are performed on only about a dozen Alpine glaciers, mostly since the 1960s. The annual mass balance of almost all Alpine glaciers is basically determined by the summer weather – extended heatwaves without summer snowfall in the accumulation areas of the glaciers are detrimental. Figure 7(b) shows the accumulated net mass balances of the Austrian Vernagtferner located in the Ötztal Alps since the glaciological year 1964/65 and of the Swiss Griesgletscher in the Lepontine

---

*Snow that has survived at least one summer melting season and has become more compact than freshly fallen snow.

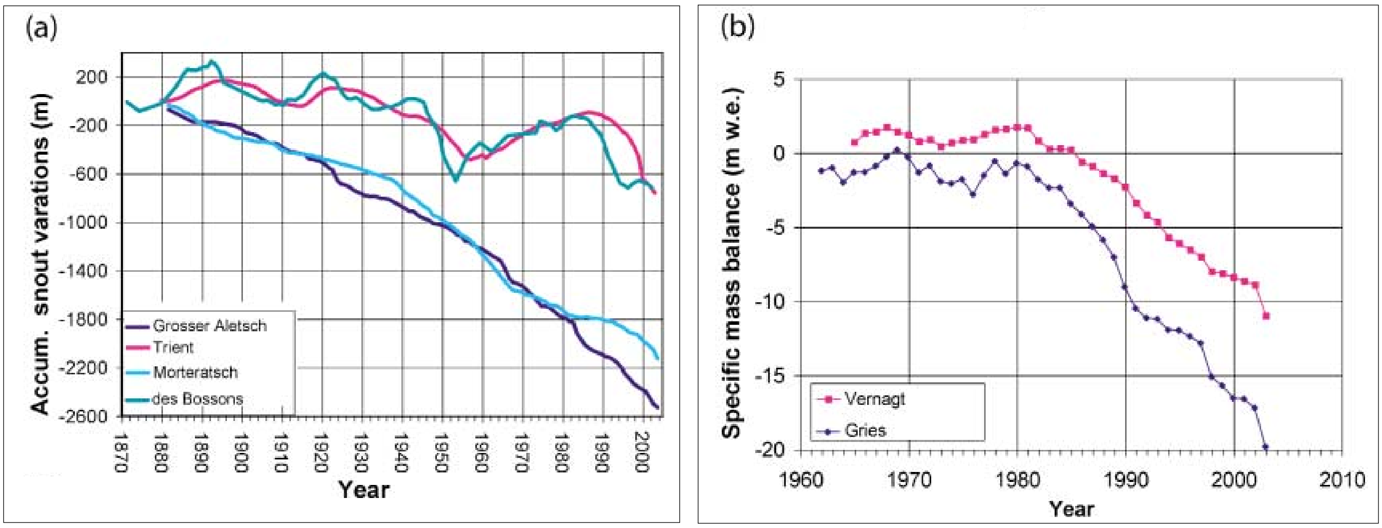

Fig. 7 (a) Annual accumulated glacier tongue variations for the Alpine glaciers Grosser Aletsch (Bernese Alps, since 1881), Morteratsch (Bernina, since 1881), Trient (Mont Blanc, since 1880), and des Bossons (Mont Blanc, since 1871) until 2003. (b) Annual accumulated net specific mass balance of Vernagtferner (Ötztaler Alps) and Griesgletscher (Lepontine Alps), starting in the glaciological years 1964/65 and 1961/62, respectively, and ending in 2002/03.

Alps since 1961/62. The mass losses of 2.13 and 2.63 m w.e., respectively, in 2002/03 stand out in the time-series. Grazzini *et al.* (2003) state that the volume of Alpine glaciers reduced by about 5–10% in 2003 alone. The extreme glacier melt in the Alps prevented the river flows of the Danube and Rhine from attaining even lower values.

The mass balance of the Vernagtferner and the Griesgletscher was near balance until early 1985. Since then, the mass balances were mostly negative with the extreme years being 2002/03, 1997/98 and 1990/91. Since the beginning of measurements the Vernagtferner and the Griesferner lost 11 and 19.5 m w.e., respectively. Assuming a density of glacier ice of 910 kg m^{-3}, this corresponds to a thinning of the glaciers of about 12 and 21.4 m respectively. Another notable feature is the fact that 2002/03 is the first glaciological year since the beginning of measurements in 1880/81 in which no advancing or stationary glacier tongue was measured in Switzerland, *i.e.* all observed glaciers were on retreat during the year considered. The behaviour of the glacier tongue is, however, the integrated response of the mass balance over a number of years, ranging up to several decades. The different response times in the snout variations depend on the glacier's size, exposure to precipitation, steepness and glacier bed geometry. Figure 7(a) shows that the largest glacier in the Alps, the Grosser Aletsch, and a large glacier in the drier interior parts of the mountains (Morteratsch, Engadin) have continuously retreated since the beginning of measurements in 1881 (see also Dent, this issue). Note that the majority of the Alpine glaciers reached a historical maximum extension at the end of the Little Ice Age around the middle of the nineteenth century. Despite an overall retreat, the two fast-reacting glaciers in the Mont Blanc group, the Bosson and the Trient, advanced around 1890, 1920, and, for the last time, during the early 1980s. These periods were characterised by more frequent cool summers, as a close inspection of the Basel temperature record in Fig. 2(a) reveals. In the mid-1980s, a rapid retreat began, which can be explained by the increased summer warmth (cf. Fig. 2(a)), especially in the months of July and August (not shown).

Some remarks on possible future trends in extreme summer weather

Understandably, the extreme year 2003 and the recent trend in summer temperature has prompted a discussion about future trends in summer heatwaves and droughts. Presently, several research projects funded by the European Union are ongoing that analyse coarse global ocean–atmosphere general circulation models and a variety of nested regional models with respect to future extreme events (*e.g.* MICE, STARDEX, and PRUDENCE projects – see http://www.cru.uea.ac.uk/projects/mps/). One such model developed in the UK is the Hadley Centre Regional Model, Version 3P (HadRM3P). The HadRM3P model was forced by the global Hadley Centre Atmospheric Model, Version 3P (HadAM3P), that has been integrated to 2100 according to the IPCC SRES A2 greenhouse-gas and aerosol-emission scenarios (Nakicenovic *et al.* 2000). Figure 8(a) displays the difference in summer days during which the 2 m maximum temperature exceeds 30 °C between the control climate period (1960–89) and the period 2070–99. It reveals that this number increases in the model at the end of the twenty-first century by about 35–48 days in the areas most affected by the 2003 summer

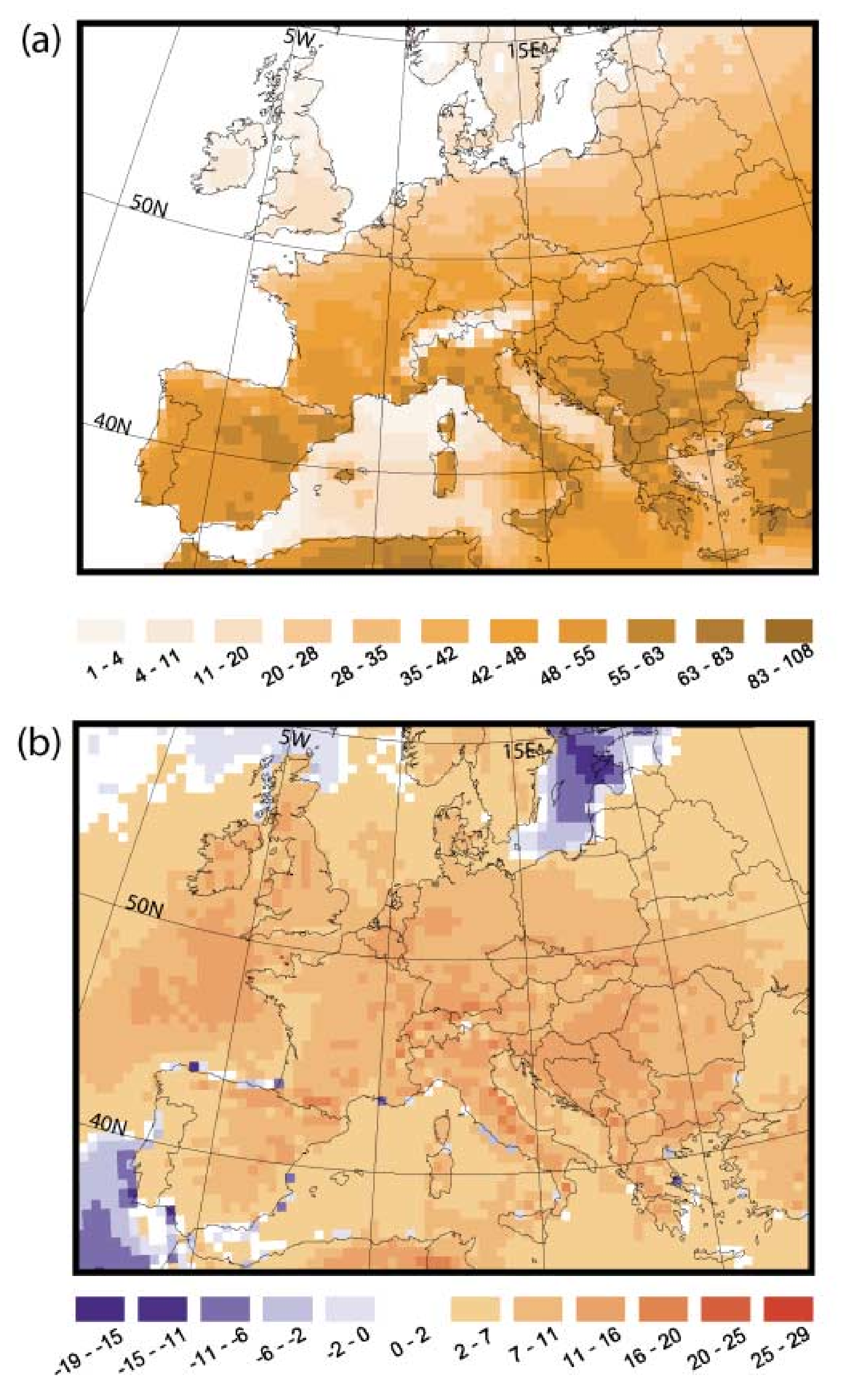

Fig. 8 (a) Increase in the number of summer days (June–August) with a maximum temperature exceeding 30 °C in the period 2070–99 compared to the control climate period (1960–89) in simulations with the regional climate model HadRM3P. (b) as (a) but for the change in the number of 'dry days', defined as model days with accumulated rainfall below 0.5 mm.

heat. In the model grid box encompassing Karlsruhe, the value rose from 20 to 64 days. These findings are consistent with the results recently described in Beniston (2004) and Schär *et al.* (2004). The latter authors used a different regional model and found that a summer like 2003 can be expected in northern Switzerland to occur every second year at the end of the twenty-first century. Moreover, the model results suggest an augmented likelihood of extended dry spells, as can be seen from the increase in the number of dry days in HadRM3P shown in Fig. 8(b). At the same time, however, they also indicate that the odds of extreme summer precipitation events will also rise in a future climate (see Ulbrich *et al.* 2003b).

Conclusions and discussion

In this paper, an analysis of the synoptic situation and the impacts of the hot, dry 2003 European summer have been presented. From some of the longest temperature records from two stations (Hohenpeissenberg and Basel-Binningen) north of the Alps, it is suggested that 2003 was the warmest summer since observations began in 1755. However, a few summers have been drier than 2003 since continuous and reliable precipitation records started in 1879 at Hohenpeissenberg (Fig. 2(b)) and in 1864 at Basel (not shown). The impacts of the heat and drought conditions on river flow, the power market and central European glaciers have been highlighted. It is argued that glacier melt prevented even lower water levels on the Danube and Rhine rivers. The discussed retreat of glaciers in the Alps since 1880 is an indirect evidence that the central European summer climate is warming, but the rate of melting has substantially increased since the mid-1980s. This is consistent with the summer temperatures at Basel (Fig. 2(a)).

In terms of the meteorological causes of the summer heatwaves and dryness, it is demonstrated that anticyclonic weather types dominated over central Europe in 2003, especially in spring and summer (cf. Fig. 6). However, our preliminary results suggest that neither the absolute anomalies of the anticyclonic flow regime nor the duration of individual anticyclonic weather patterns alone give a satisfactory explanation of the extreme surface air temperature values observed in June and August 2003. This is probably due to the fact that the intensities of irradiation, cloud cover, moist convection, and heat advection vary between different periods of the same anticyclonic GWL. It is, however, argued here that the prevalence of anticyclonic weather in spring and summer 2003 caused the overall dryness of both seasons. This in turn led to a continuing reduction in the soil moisture content and a wilting of the vegetation as the seasons progressed. These surface conditions generally favour high temperatures because they enhance the surface sensible heat flux.

The record-breaking total sunshine hours at Basel in summer 2003 support the notion of an increased short-wave radiative forcing at the surface. In conjunction with a substantial decrease in the surface latent heat fluxes due to the dry soils and wilted vegetation, the radiative forcing will have augmented the maximum temperatures, especially in August 2003. Results presented by Black *et al.* (this issue) using ground heat flux and radiation data from a field site at Reading (UK), as well as net radiation and turbulent heat fluxes, averaged over Europe, from the European Centre for Medium-Range Weather Forecasts analysis system support this view. A positive feedback between reduced soil moisture and cloudiness/moist convective activity might also be a causal factor. Furthermore, Black *et al.* (this issue) give evidence that strong anticyclonic subsidence prevailed over the Paris area during the peak of the August heatwave, thereby inhibiting cloud formation. They argue that the above-mentioned local impacts on the surface energy budget are the major explanatory factor for the August heatwave since airmass advection was weak as a result of slack pressure gradients. Extending their findings, the investigations presented here indicate that advection of anomalously warm air from the south-west played a role in the extreme June warmth.

The contrasting summer weather in 2002 – extreme floods – and 2003 – heat and drought – has stimulated discussions about the possibility that these events are indicators of an enhanced anthropogenic climate change. Schär *et al.* (2004) mention that the temperature anomalies in Switzerland measured in 2003 can be expected to occur only on the order of once in several thousand years, provided that stationarity in the historical time-series is assumed. If, on the other hand, the ongoing climate change results in an increased variability around a slowly increasing mean, as some climate models indicate, the 2003 event is at present already more likely than the traditional statistical analysis of observational records would yield (Schär *et al.* 2004). The latter method to estimate recurrence intervals of rare events is based on the assumption of no changes in the shape of the probability density functions fitted to the observations. It should also be emphasised that the summer 2003 temperatures might have been exceeded in the pre-instrumental past. Patzelt (2004) speculated that the summers of 1616 and especially 1540 might have been warmer. The contrasting extremes of summer 2002 and 2003 cannot by themselves be used to infer that humans have influenced climate but, if the climate change simulations under future emissions scenarios prove to be realistic, the hot, dry summer of 2003 gives us an idea of things to come.

Acknowledgements

We wish to acknowledge the comments of John Methven and an anonymous reviewer which helped to improve the manuscript. The research reported here was partly funded by the EU Project MICE (Modelling the Impacts of Climate Extremes) under grant EVK2-CT-2002-00118. We would like to acknowledge H. Engel from the Bundesanstalt für Gewässerkunde for providing the river flow data and Paul Schlaak (Berlin) for contributing the monthly temperature, precipitation and sunshine data for Basel-Bininingen. We are grateful to Ludwig Braun from the Bavarian Commission of Glaciology and Andreas Bauder from the Laboratory of Hydraulics, Hydrology and Glaciology at the Swiss Federal Institute of Technology Zürich for contributing the mass balance data of the Vernagtferner and the Griesgletscher. Christian Vincent from the Laboratoire de Glaciologie et Geophysique de l'Environment kindly sent us the glacier tongue variations of some French glaciers. Prof. Wehry from the Free University of Berlin furnished the CLIMAT reports to the authors. We are indebted to Volker Ermert for computing Fig. 1.

References

APX (2003) *APX Monthly Report,* **17,** September 2003. Available online from http://www.apx.nl/marketresults/monthly/apx_monthly_september03.pdf

Bader, S. and Zbinden, L. (2003) *Aussergewöhnlicher Hitzrekord.* MeteoSchweiz report, available online in German from http://www.meteoschweiz.ch/de/Wissen/Rekorde/tempMaxJuni03.shtml

Bader, S. and Zgraggen, L. (2003) *Am Montag an der Alpensüdseite 41.5 °C Grad gemessen*. MeteoSchweiz report, available online in German from http://www.meteoschweiz.ch/de/Wissen/Rekorde/rekordtemp2003.shtml

Belz, J. U., Engel, H. and Krahe, P. (2004) *Das Niedrigwasser in Deutschlands Stromgebieten*. Bundesanstalt für Gewässerkunde report, available online in German from http://www.wasserblick.net/servlet/is/12133/nw-bericht.pdf?command=downloadContent&filename=nw-bericht.pdf

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,** pp. 2022–2026, L02202, doi:10.1029/2003GL018857

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 online from http://www.copa-cogeca.com/pdf/pocc_03_78i4_1e.pdf

Fricke, W. (2003) *GAW Brief des Deutschen Wetterdienstes*, No. 18. Available online from http://www.dwd.de/de/FundE/Observato/ MOHP/hp2/gaw/gaw_briefe/-gaw_brief_018.pdf

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

Grazzini F., Ferranzi, L., Lalaurette, F. and Vitart, F. (2003) The exceptional warm anomalies of summer 2003. *ECMWF Newsletter,* **99,** pp. 2–8

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. (1996) The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.*, **77,** pp. 437–471

Nakicenovic, N. (lead author) (2000) *IPCC special report on emissions scenarios.* Cambridge University Press

Patzelt, G. (2004): Der Sommer 2003 – extrem aber nicht einmalig. *Alpenverein 01/04,* **59,** pp. 6–7

Schär, C., Vidale, P. L., Lüthi, D., Frei, C., Häberli, C., Lininger, M. A. and Appenzeller, C. (2004) The role of increasing temperature variability in European summer heatwaves. *Nature*, **427,** pp. 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. Z.* **13,** pp. 343–347

Ulbrich, U., Brücher, T., Fink, A. H., Leckebusch, G. C., Krüger, A. and Pinto, J. G. (2003a) The central European floods of August 2002: Part 1 – Rainfall periods and flood development. *Weather*, **58,** pp. 371–377

—— (2003b) The central European floods of August 2002: Part 2 – Synoptic causes and considerations with respect to climate change. *Weather*, **58,** pp. 434–442

WHO (2003) *Health effects of extreme weather events: WHO's early findings to be presented at the World Climate Change Conference.* Available online from http://www.euro.who.int/mediacentre/PR/2003/20030929_1

The online documents referenced above are mirrored under http://www.meteo.uni-koeln.de/content/forschung/klimadiagnose/CEsummerheat2003.html

Correspondence to: Dr Andreas H. Fink, Institute of Geophysics and Meteorology, University of Cologne, D-50923 Köln, Germany. e-mail: fink@meteo.uni-koeln.de

doi: 10.1256/wea.73.04

A barge navigating very shallow waters of the River Rhine near Boppard, 21 September 2003 (© G. Spence)