GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L06707, doi:10.1029/2006GL029068, 2007

Contribution of land-atmosphere coupling to recent European summer heat waves

E. M. Fischer,[1] S. I. Seneviratne,[1] D. Lüthi,[1] and C. Schär[1]

Received 22 December 2006; revised 16 February 2007; accepted 23 February 2007; published 24 March 2007.

[1] Most of the recent European summer heat waves have been preceded by a pronounced spring precipitation deficit. The lack of precipitation and the associated depletion of soil moisture result in reduced latent cooling and thereby amplify the summer temperature extremes. In order to quantify the contribution of land-atmosphere interactions, we conduct regional climate simulations with and without land-atmosphere coupling for four selected major summer heat waves in 1976, 1994, 2003, and 2005. The coupled simulation uses a fully coupled land-surface model, while in the uncoupled simulation the mean seasonal cycle of soil moisture is prescribed. The experiments reveal that land-atmosphere coupling plays an important role for the evolution of the investigated heat waves both through local and remote effects. During all simulated events soil moisture-temperature interactions increase the heat wave duration and account for typically 50–80% of the number of hot summer days. The largest impact is found for daily maximum temperatures during heat wave episodes.
Citation: Fischer, E. M., S. I. Seneviratne, D. Lüthi, and C. Schär (2007), Contribution of land-atmosphere coupling to recent European summer heat waves, *Geophys. Res. Lett.*, *34*, L06707, doi:10.1029/2006GL029068.

1. Introduction

[2] Recent summer heat waves had strong socio-economic impacts in different parts of Europe. The record-breaking 2003 heat wave increased mortality by around 35,000 heat-related deaths across Europe [e.g., *Vandentorren et al.*, 2004; *Hémon and Jougla*, 2004; *Schär and Jendritzky*, 2004] and resulted in large financial losses due to crop shortfall and forest fires. Similar albeit weaker impacts have been observed during the 1976 heat wave, which caused an average mortality increase of 20–30% in Birmingham [*Ellis et al.*, 1980], and during the 1994 heat wave, which led to a statistical excess over mean mortality rates of about 10% in Belgium [*Sartor et al.*, 1995].

[3] These recent heat waves highlight the importance of a detailed understanding of the key processes and feedbacks contributing to such extreme events. Heat waves are generally associated with quasi-stationary anticyclonic circulation anomalies. These anticyclonic anomalies produce subsidence, clear skies, warm-air advection, and prolonged hot conditions at the surface [*Black et al.*, 2004; *Meehl and Tebaldi*, 2004; *Xoplaki et al.*, 2003].

[4] However, several recent studies have highlighted the role of land-atmosphere interactions in addition to circulation patterns for the occurrence of heat waves. *Fischer et al.* [2007] presented a detailed analysis of the contribution of soil moisture–atmosphere interactions to the 2003 European summer heat wave. They performed sensitivity simulations and demonstrated that soil moisture anomalies had a substantial impact upon the strength of the 2003 heat wave and also affected the extent of the geopotential height anomalies. Consistent with these results, *Zaitchik et al.* [2006] highlighted the important role of land-atmosphere feedbacks upon the 2003 heat wave using satellite imagery and meteorological station data. More general, *Vautard et al.* [2007] found that the 10 warmest European summers over the past five decades were in average preceded by reduced winter and spring precipitation frequency around the Mediterranean. Using statistical models, *Della-Marta et al.* [2007] suggested that the consideration of January to May Mediterranean precipitation (and thus spring soil moisture anomalies) improves the skill of statistical seasonal predictions during the summer season.

[5] As regards climate change, model simulations indicate that extraordinary hot summers over Europe and other mid-latitudinal regions will become more frequent, more intense and longer lasting in the future [e.g., *Meehl and Tebaldi*, 2004; *Giorgi et al.*, 2004], partly associated with an increase in interannual temperature variability [e.g., *Schär et al.*, 2004; *Vidale et al.*, 2007]. *Seneviratne et al.* [2006] found that the latter variability increase is strongly related to land-atmosphere coupling.

[6] The present study investigates the contribution of land-atmosphere interactions to the statistics of daily maximum temperatures. This is particularly relevant for heat wave impacts, such as increases in mortality, which are more sensitive to the number of (consecutive) days with extraordinary high temperatures than to seasonal mean temperature anomalies. In order to investigate the role of land-atmosphere coupling for heat wave strength and duration, we perform pairs of simulations for four of the most extreme European heat wave events of the past decades. These four extreme events have different temporal and spatial structures. However, they all had a substantial impact on society and ecosystems.

2. Experimental Model Setup

2.1. Model Details

[7] The Climate High-Resolution Model (CHRM) version 2.3 [*Vidale et al.*, 2003] is a state-of-the-art regional climate model, using a regular latitude/longitude grid ($0.5° \times 0.5°$) with a hybrid sigma pressure coordinate with 20 vertical levels and three active soil layers. The CHRM has been

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland.

0094-8276/07/2006GL029068

validated regarding its ability to represent natural variability on different time scales [e.g., *Vidale et al.*, 2003; *Kjellström et al.*, 2007]. The current model version has previously been used in a number of sensitivity studies [e.g., *Hohenegger and Vidale*, 2005; *Fischer et al.*, 2007] and climate scenario studies [*Schär et al.*, 2004; *Seneviratne et al.*, 2006; *Vidale et al.*, 2007].

2.2. Experimental Design

[8] The computational domain used in this study covers Europe and the north-eastern Atlantic with a horizontal resolution of about 56 km. We perform a 46-year CHRM simulation covering the period 1960–2005 with a coupled land-surface scheme (hereinafter referred to as CL simulation). The simulation is initialized on January 1, 1959, allowing for one year spin-up time. In the first part (1959–2001), the simulation is driven with boundary conditions and SSTs from the ERA-40 reanalysis, and in the second part (2002–2005) with corresponding data from the ECMWF operational analysis.

[9] We repeated the simulations for the years 1976, 1994, 2003 and 2005 with the same model set-up but uncoupling the soil moisture from the atmospheric evolution (hereinafter referred to as UCL simulation) using the same approach as *Seneviratne et al.* [2006]. In the UCL simulations, soil moisture at each time step is prescribed by its climatology represented by the average annual cycle of the CL simulation (1960–2005). The comparison of the pairs of CL and UCL simulations allows to isolate the contribution of land-atmosphere coupling upon the investigated heat waves.

2.3. Measures of Daily Temperature Extremes

[10] In order to determine the severity of a heat wave we use the following two measures of temperature extremes: (1) number of hot days (NHD) and (2) maximum heat wave duration (HWD). NHD is defined as the number of days where the temperature exceeds the long-term 90th percentile of daily maximum temperatures. The background statistics for each summer day is calculated from samples of 15 days (7 days before and 7 days after) over the period 1960–2005. For the CL and UCL simulations, the 90th percentile is derived from the CL runs, while for the observations the ECAD dataset (see section 3) is used. The HWD is defined as the maximum number of consecutive hot days. Both indices are calculated over the 92-day period June–August [see also *Della-Marta et al.*, 2007].

3. Observational Data

[11] We use the Full Data Reanalysis Product [*Rudolf et al.*, 1994] of the Global Precipitation Climatology Centre (GPCC) to analyze the spring precipitation anomalies. This data set (resolution $0.5^\circ \times 0.5^\circ$) covers the period 1951–2004 and is based on quality-controlled in-situ observations. Since this product ends in 2004, the GPCC Monitoring Product is used for the 2005 event.

[12] The NASA GISS Surface Temperature Analysis (GISTEMP) [*Hansen et al.*, 1999] is used to visualize temperature anomaly patterns in 1976, 1994, 2003, and 2005. GISTEMP is a global analysis of land surface temperature and SSTs ($1^\circ \times 1^\circ$) using observational station data as input.

[13] In order to validate the simulated extreme temperature indices NHD and HWD we use daily maximum temperature observations from the European Climate Assessment and Dataset project (ECAD) [*Klein Tank et al.*, 2002].

4. Four Recent Major European Heat Waves

4.1. Temperature and Precipitation Characteristics

[14] Here, we discuss the main characteristics of the four heat waves considered in terms of observed temperature and precipitation anomalies. The four heat waves have been selected based on their well-known societal and ecological impacts, and on their good documentation in the literature. The events have not been chosen because of any special land surface conditions (e.g., low soil moisture) or because of temperature exceedances over a single representative region (e.g., central Europe). The latter criterion would exclude small-scale events such as the 1976 heat wave with large temperature contrasts (hot British Isles, cold southern Europe).

[15] The 1976 summer heat wave was confined to northern France and southern England, where the mean summer (JJA) temperature 1970–2000 was exceeded by more than 2°C (Figure 1a) and up to more than 35 hot days were observed (Figure 2a). Maximum temperatures were reached between June 23 and July 8, when temperatures exceeded 32°C at some stations in southern England and 35°C over large parts of northern France on 16 consecutive days [*Ratcliffe*, 1976, 1978; *Shaw*, 1977]. The 1976 heat wave has been the culmination of an unprecedented 16-month period with strong precipitation deficits (see months FMAM in Figure 1e), which started as early as May 1975. Averaged over the 16-month period, precipitation was less than 50% of the long-term mean at many stations in southern England and northern Bretagne [*Morris and Ratcliffe*, 1976].

[16] The 1994 heat wave was somewhat weaker on the seasonal scale with JJA temperature anomalies of around 2°C (Figure 1b) and NHD between 15–30 (Figure 2b) over central Europe and parts of the Mediterranean. During the culmination of the heat wave in July, anomalies amounted to more than 4°C over southern Scandinavia and central Europe. In August weaker anomalies of about 2°C were recorded further south around the Mediterranean. In the case of the 1994 heat wave, negative FMAM precipitation anomalies were only observed over the western Iberian Peninsula and Italy (Figure 1f). Over central Europe precipitation was higher than average in the same period, but anomalously low in June, the month before the actual heat wave.

[17] During summer 2003 a record-breaking heat wave affected central Europe and the Mediterranean region. Mean summer temperatures exceeded the long-term average by more than 3°C (Figure 1c) over large areas and by over 5°C regionally [*Schär et al.*, 2004; *Luterbacher et al.*, 2004; *Beniston*, 2004; *Black et al.*, 2004; *Fischer et al.*, 2007]. Two distinct periods of exceptional heat developed in June and in the first half of August. Over parts of France and Switzerland observed NHD amount to 40–60 during JJA (≈5–6 times the long-term average, Figure 2c). The persistent precipitation deficit (Figure 1g) in the months between mid-February and August 2003 and the excess in total net radiation in late winter and spring 2003 strongly

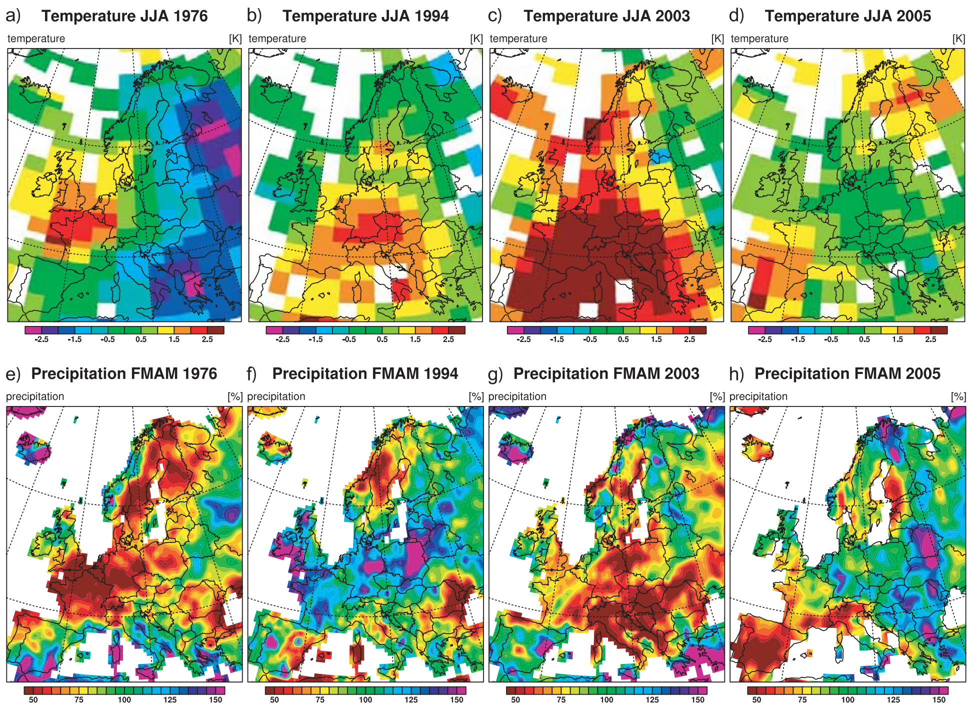

Figure 1. Observed summer mean temperature anomalies in JJA (a) 1976, (b) 1994, (c) 2003, and (d) 2005 with respect to the climatological mean over 1970–2000 (NASA GISTEMP analysis). Observed precipitation (GPCC) percentages of normals averaged over the months February–May in (e) 1976, (f) 1994, (g) 2003, and (h) 2005.

contributed to anomalous soil moisture depletion and drought conditions during the 2003 heat wave [*Fischer et al.*, 2007].

[18] The 2005 summer heat wave was confined to the Iberian Peninsula and southern France, where JJA temperature anomalies amounted to about 1.5–2.5°C (Figure 1d). The heat wave was most pronounced in June with monthly mean temperature departures of almost 3.5°C. The exceptionally dry conditions over the Iberian Peninsula started long before the actual 2005 heat wave [*Garcia-Herrera et al.*, 2007] with anomalously low precipitation in all months between November 2004 and September 2005.

4.2. Validation of CHRM Simulations

[19] The CL simulations capture the observed temperature anomaly patterns (Figures 1a–1d) and the observed NHD (Figures 2a–2d) with notable accuracy. At the fringes of the strongest anomalies, the NHD are somewhat underestimated over southern Scandinavia in 1994, over Germany and the Balkans in 2003, and over northern Scandinavia in 2005.

[20] The observed 4-month spring (FMAM) precipitation percentages have been reasonably reproduced in the regional climate simulations (not shown). The precipitation deficit in 1976 is well captured over northern France and southern UK, however it extends too far to the east. The simulated spring precipitation anomaly patterns in 1994, 2003, and 2005 compare well with observations, except for a weak overestimation over Germany in 2003 and 2005. The reasonable simulation of the spring precipitation anomalies provides confidence in the realistic representation of the soil moisture anomalies in early summer, which is an important quantity for the following analysis.

5. The Role of Land-Atmosphere Coupling

[21] In this section we analyze the contribution of land-atmosphere coupling to the strength, duration and spatial extent of the four selected heat wave episodes. To this end we compare the simulated NHD and HWD in the coupled (CL) against the uncoupled (UCL) simulations. In terms of the classification given by *Rowell and Jones* [2006], this difference represents a combination of two mechanisms: one-way effect of spring soil moisture anomalies on summer temperatures (a cause and effect relationship) and two-way summer soil moisture-temperature/precipitation interactions (a feedback loop). As we have not separated these two factors, we refer to their combination as coupling.

[22] Figure 2 shows the NHD during the heat waves 1976, 1994, 2003, and 2005 in the observations (Figures 2a–2d), the CL simulations (Figures 2e–2h) and the UCL (Figures 2i–2l) simulations. During all four events the NHD as well as the HWD (not shown) is substantially reduced if the soil moisture is prescribed by climatological mean conditions (UCL simulations). Generally, the differences in NHD and HWD between CL and UCL are largest over regions affected by pronounced local summer drought conditions in CL. However, in addition to this local effect, drought conditions may have remote effects outside the actual drought regions. The temperature amplification through land-atmosphere coupling is found to be substantially stronger for daily maximum temperatures (2–3°C) than for mean (1.5–2°C) and minimum temperatures (0–1°C).

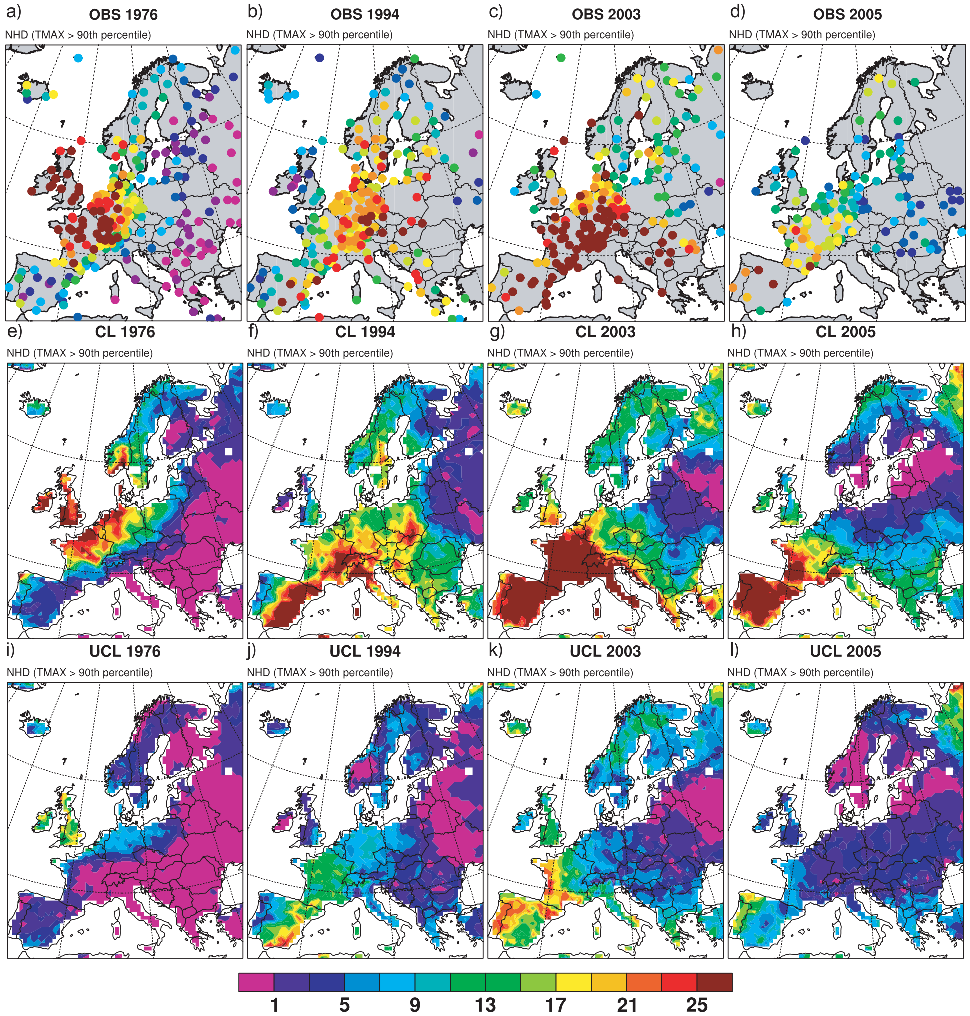

Figure 2. Number of hot days (NHD) derived from (a–d) observed ECAD daily maximum temperature series, and (e–h) the simulations with (CL) and (i–l) without land-atmosphere coupling (UCL) during the summers (JJA) 1976, 1994, 2003, and 2005.

Hence, in addition to a general warming the land-atmosphere interactions contribute to an enhanced diurnal temperature range.

[23] In the following, we discuss and compare the CL and UCL simulations for the four individual heat waves. In summer 1976 preceding soil moisture anomalies contributed to a substantially higher NHD in the CL than in UCL simulation (Figures 2e and 2i). The difference is most dominant over northern France and to somewhat lesser extent over the British Isles. While the NHD in UCL still amounts to 15–20 over the British Isles, it is near zero over some regions in France and southern Scandinavia. Note that all these areas show distinct drought conditions in the CL simulation. However, the anticyclonic circulation anomaly, which is centered over the British Isles, forces a relatively large NHD even in the absence of anomalous local drying. In addition to an increase of NHD, land-atmosphere interactions result in a slightly longer period of consecutive hot days (higher HWD, not shown). On daily time-scale, the strongest amplification of temperatures is found during the hottest episode between June 23 and July 8 over the British Isles and northern France. *Ratcliffe* [1978] already pointed out that the drought conditions themselves may have contributed to higher persistence of the heat wave. He estimated that about 90% of the surface net radiation was transferred to sensible heat and only 10% to latent heat flux (with a 60%/40% ratio in an average year). Furthermore, he suggested that due to the highly anomalous 1000–500 hPa thickness patterns, frontal systems may have been deflected northwards and inhibited to penetrate to the British Isles.

[24] On average the effect of land-atmosphere coupling in JJA 1994 is somewhat less pronounced (Figures 2f and 2j). However, a distinct difference in NHD is found around the Mediterranean, especially north of the Gulf of Genova. Most of this difference may be attributed to local drying in CL, which was strongest in the course of the summer itself, in June and July. This resulted in strongly limited evaporation and a large NHD over northern Italy in August. Interestingly the NHD differs also over parts of Germany and France, where no spring and only weak early summer precipitation deficits are found in CL. In this case the NHD is only weakly affected by local effects of reduced latent

cooling but to a higher extent by remote effects through changes in circulation.

[25] In the CL simulation the anomalous 500 hPa ridge situated over the Mediterranean and central Europe is enhanced and reaches further North than in UCL (not shown). We suggest that through this feedback on mid-tropospheric circulation the soil moisture deficit around the Mediterranean may have a remote effect on temperature [see also *Fischer et al.*, 2007]. Note, that the soil moisture-circulation feedback in our experiment might be constrained by the prescription of the lateral boundary conditions. *Vautard et al.* [2007] suggested that the northward drought progression results from efficient atmospheric transport of anomalously warm and dry air by prevailing southerly winds. Other remote effects may relate to moisture transport and cloud cover.

[26] The 2003 heat wave is the most pronounced event, both in space and time, showing maximum NHD over large parts of western and central Europe (Figure 2c). The uncoupling of the land-atmosphere system in this year has a significant impact: the NHD is substantially lower in the UCL simulation (typically 50–80%), especially in eastern France and around the Alpine region (Figure 2k). The average HWD over central Europe corresponds to only 6 days in UCL instead of 13 days in CL (not shown). On a daily time-scale the amplifying effect is most pronounced during the hottest episode (August 2–12) and hardly noticeable during comparatively cool days. Similarly as in 1994, there is a change in circulation (not shown) over the drought region. This feedback effect [*Fischer et al.*, 2007] results in a strengthening and a slight eastward shift of the 500 hPa height anomaly. Despite the strong land-atmosphere interactions, a substantial portion of the NHD still remains in the UCL simulation over western France and the Iberian Peninsula, due to the extraordinary strong anticyclonic circulation anomaly and the associated net radiation excess. Generally, the influence of the land-atmosphere coupling is much weaker in maritime regions near the French and Portuguese west coasts.

[27] The effect of land-atmosphere coupling on the NHD and HWD is most pronounced during the 2005 heat wave (Figures 2h and 2l). The extremely dry conditions in the CL simulation result in an extraordinary large NHD over the Iberian Peninsula and southwestern France. Again the effect of land-atmosphere coupling is strongest in the continental parts and to lesser extent along the coasts. The effect on daily temperature extremes is most pronounced in June and early July, mostly because the Iberian Peninsula experiences very dry August conditions even in a normal climatological mean summer.

6. Conclusions

[28] The amplifying effect of land-atmosphere coupling on temperature extremes has been analyzed during four recent major heat waves by means of observational data and regional climate simulations.

[29] The heat waves in 1976, 2003, and 2005 were preceded by a mean precipitation deficit during at least four antecedent months. At the same time the coupled (CL) simulations show a distinct excess in surface net radiation leading to enhanced evaporation, particularly in the spring of 1976 and 2003. These two factors provide strong evidence for the important role of preceding dry soils in driving/enhancing the major heat wave episodes in 1976, 2003, and 2005. In the case of 1994 the spring deficit was constrained to regions around the Mediterranean. Over central Europe precipitation was anomalously low only in June 1994, the month before the actual heat wave.

[30] The regional climate model experiments reveal a major contribution of land-atmosphere interactions to the spatial and temporal extent of all four heat waves. In all the cases considered, the difference between coupled and uncoupled simulations is considerably larger than the model biases. Land-atmosphere interactions over the drought regions account for typically 50–80% of the NHD. This is mainly due to local effects through the limitation of evaporation (and compensation by sensible heat flux) due to drought conditions. Additionally drought conditions may have remote effects on areas around or outside the actual drought region, through changes in atmospheric circulation and advection of air masses. These mechanisms enhance the anticyclonic circulation over or slightly downstream of a drought anomaly. However, a larger computational domain or global simulations would be needed to further explore this effect.

[31] Land-atmosphere coupling is found to increase mean, maximum as well as to lesser extent the minimum temperatures averaged over anomalously warm summers. The effect does not only enhance seasonal mean anomalies, but in particular amplifies daily temperature extremes during the hottest summer days. This is of high importance, since maximum temperatures as well as the duration of these extreme episodes are critical measures for the impact on ecosystem as well as public health.

[32] **Acknowledgments.** We thank the two anonymous reviewers for their valuable comments on the manuscript. This research was supported by the Swiss National Science Foundation (NCCR Climate) and the 5th and 6th Framework Programme of the European Union (projects PRUDENCE and ENSEMBLES). The simulations were performed at the Swiss National Supercomputing Centre (CSCS) in Manno.

References

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, doi:10.1029/2003GL018857.

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

Della-Marta, P. M., J. Luterbacher, H. von Weissenfluh, E. Xoplaki, M. Brunet, and H. Wanner (2007), Summer heat waves over western Europe 1880–2003: Their relationship to large scale forcings and predictability, *Clim. Dyn.*, in press.

Ellis, F., H. Prince, G. Lovatt, and R. Whittington (1980), Mortality and morbidity in Birmingham during the 1976 heat wave, *Q. J. Med.*, *49*, 1–8.

Fischer, E. M., S. I. Seneviratne, P. L. Vidale, D. Lüthi, and C. Schär (2007), Soil moisture-atmosphere interactions during the 2003 European summer heat wave, *J. Clim.*, in press.

Garcia-Herrera, R., D. Paredes, R. M. Trigo, I. F. Trigo, E. Hernández, D. Barriopedro, and M. A. Mendes (2007), The outstanding 2004-2005 drought in the Iberian Peninsula: associated atmospheric circulation, *J. Hydrometeorol.*, in press.

Giorgi, F., X. Q. Bi, and J. Pal (2004), Mean, interannual variability and trends in a regional climate change experiment over Europe II: Climate change scenarios (2071–2100), *Clim. Dyn.*, *23*(7–8), 839–858.

Hansen, J., R. Ruedy, J. Glascoe, and M. Sato (1999), GISS analysis of surface temperature change, *J. Geophys. Res.*, *104*, 30,997–31,022.

Hémon, D., and E. Jougla (2004), Surmortalité liée à la canicule d août 2003 (in French), report, 76 pp., L'Inst. Natl. de la Santé et de la Rech. Médicale, Paris.

Hohenegger, C., and P. l. Vidale (2005), Sensitivity of the European climate to aerosol forcing as simulated with a regional climate model, *J. Geophys. Res.*, *110*, D06201, doi:10.1029/2004JD005335.
Kjellström, E., L. Bärring, D. Jacob, R. Jones, G. Lenderink, and C. Schär (2007), Modelling daily temperature extremes: Recent climate and future changes over Europe, *Clim. Change*, in press.
Klein Tank, A., et al. (2002), Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment, *Int. J. Climatol.*, *22*(12), 1441–1453.
Luterbacher, J., D. Dietrich, E. Xoplaki, M. Grosjean, and H. Wanner (2004), European seasonal and annual temperature variability, trends, and extremes since 1500, *Science*, *303*, 1499–1503.
Meehl, G. A., and C. Tebaldi (2004), More intense, more frequent, and longer lasting heat waves in the 21st century, *Science*, *305*, 994–997.
Morris, R. M., and R. Ratcliffe (1976), Under the weather, *Nature*, *264*, 4–5.
Ratcliffe, R. A. S. (1976), The hot spell of late June–early July 1976, *Weather*, *31*, 355–357.
Ratcliffe, R. A. S. (1978), Meteorological aspects of the 1975–76 drought, *Proc. R. Soc. London., Ser. A*, *363*, 3–20.
Rowell, D. P., and R. G. Jones (2006), Causes and uncertainty of future summer drying over Europe, *Clim. Dyn.*, *27*, 281–299.
Rudolf, B., H. Hauschild, W. Rueth, and U. Schneider (1994), Terrestrial precipitation analysis: Operational method and required density of point measurements, in *Global Precipitations and Climate Change*, *NATO ASI Ser. 1*, vol. 26, Springer, New York.
Sartor, F., R. Snacken, C. Demuth, and D. Walckiers (1995), Temperature, ambient ozone levels, and mortality during summer, 1994, in Belgium, *Environ. Res.*, *70*(2), 105–113.
Schär, C., and G. Jendritzky (2004), Hot news from summer 2003, *Nature*, *432*, 559–560.
Schär, C., P. L. Vidale, D. Lüthi, C. Frei, C. Häberli, M. A. Liniger, and C. Appenzeller (2004), The role of increasing temperature variability in European summer heatwaves, *Nature*, *427*(322), 332–336.
Seneviratne, S. I., D. Lüthi, M. Litschi, and C. Schär (2006), Land-atmosphere coupling and climate change in Europe, *Nature*, *443*, 205–209.
Shaw, M. S. (1977), The exceptional heat wave of 23 June to 8 July 1976, *Meteorol. Mag.*, *106*(1264), 329–346.
Vandentorren, S., F. Suzan, S. Medina, M. Pascal, A. Maulpoix, J. C. Cohen, and M. Ledrans (2004), Mortality in 13 French cities during the August 2003 heat wave, *Am. J. Public Health*, *94*(9), 1518–1520.
Vautard, R., P. Yiou, F. D'Andrea, N. d. Noblet, N. Viovy, C. Cassou, J. Polcher, P. Ciais, M. Kageyama, and Y. Fan (2007), Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit, *Geophys. Res. Lett.*, doi:10.1029/2006GL028001, in press.
Vidale, P. L., D. Lüthi, C. Frei, S. I. Seneviratne, and C. Schär (2003), Predictability and uncertainty in a regional climate model, *J. Geophys. Res.*, *108*(D18), 4586, doi:10.1029/2002JD002810.
Vidale, P., D. Lüthi, R. Wegmann, and C. Schär (2007), European climate variability in a heterogeneous multi-model ensemble, *Clim. Change*, in press.
Xoplaki, E., J. F. González-Rouco, J. Luterbacher, and H. Wanner (2003), Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs, *Clim. Dyn.*, *20*(7), 723–739.
Zaitchik, B., A. K. Macalady, L. R. Bonneau, and R. B. Smith (2006), Europe's 2003 heat wave: A satellite view of impacts and land-atmosphere feedbacks, *Int. J. Climatol.*, *26*(6), 743–769.

E. M. Fischer, D. Lüthi, C. Schär, and S. I. Seneviratne, Institute for Atmospheric and Climate Science, ETH Zurich, Universitaetsstrasse 16, CH-8092 Zurich, Switzerland. (erich.fischer@env.ethz.ch)