The influence of oceanic conditions on the hot European summer of 2003

Emily Black · Rowan Sutton

Abstract The summer of 2003 was the hottest on record throughout much of Europe. Understanding how the event developed and the factors that contributed to it may help us improve seasonal forecasting models and assess the risk of such events in the future. This study uses atmosphere-only model integrations and observed data to investigate the potential predictability of the climate anomalies, and in particular the impact that the warming in the Indian Ocean and Mediterranean Sea had on the development of the temperature anomalies. The model results suggest that the temperature anomalies were potentially predictable and that both Indian Ocean and Mediterranean sea surface temperature anomalies contributed to the development of the observed warm and dry anomalies over Europe. Furthermore, it was found that, in the model, the Mediterranean anomalies contributed most strongly to the warming in June and July and the Indian Ocean anomalies enabled the positive temperature anomalies to persist into August. Previously published work has described the role of the Indian monsoon in modulating the seasonal cycle in rainfall over Europe. Comparison with this work suggests a mechanism by which warming in the Indian Ocean may have contributed to the persistence of the temperature and precipitation anomalies into August.

E. Black (✉) · R. Sutton
Centre for Global Atmospheric Modelling,
University of Reading, Earley Gate,
Reading RG6 6BB, UK
e-mail: emily@met.reading.ac.uk

1 Introduction

The 2003 summer was the hottest on record over much of Europe (see for example Stott et al. 2004; Schaer et al. 2004). Investigating its evolution represents a rare opportunity to explore dynamic mechanisms in the noisy European climate, because there were strong signals in several meteorological variables including rainfall, surface air temperature and sea surface temperature (SST). Furthermore, understanding the causes of the event may enable us to draw conclusions about the likelihood of its recurring and the possibility of our being able to predict such events months or seasons ahead.

In 2003, temperatures in Europe were well above average from the beginning of May until the end of August. The evolution of the event from June to August is shown in Fig. 1 and the June–August SST anomalies relative to the 1970–1999 climate are shown in Fig. 2. At the beginning of May, temperatures were raised over central and western Europe to 30°C (303 K). The temperature anomalies persisted throughout the season, weakening somewhat during July, but reinvigorating during August, when the highest temperatures of the season were experienced. The circulation and surface temperature anomalies were accompanied by strong rainfall anomalies over much of Europe. In June, there were negative rainfall anomalies almost everywhere in western Europe, with the strongest anomalies in south and the east. In July, the rainfall anomalies were generally weaker, and in westernmost and easternmost regions were positive. In August, there were strong negative rainfall anomalies everywhere except on the Iberian Peninsula. The surface air temperature anomalies were accompanied by

Fig. 1 Evolution of 2 m air temperature (*top row*), precipitation (middle row) and 500 mb geopotential height (*bottom row*) for June, July and August (*left to right columns*). The contour interval for geopotential height is 25 m
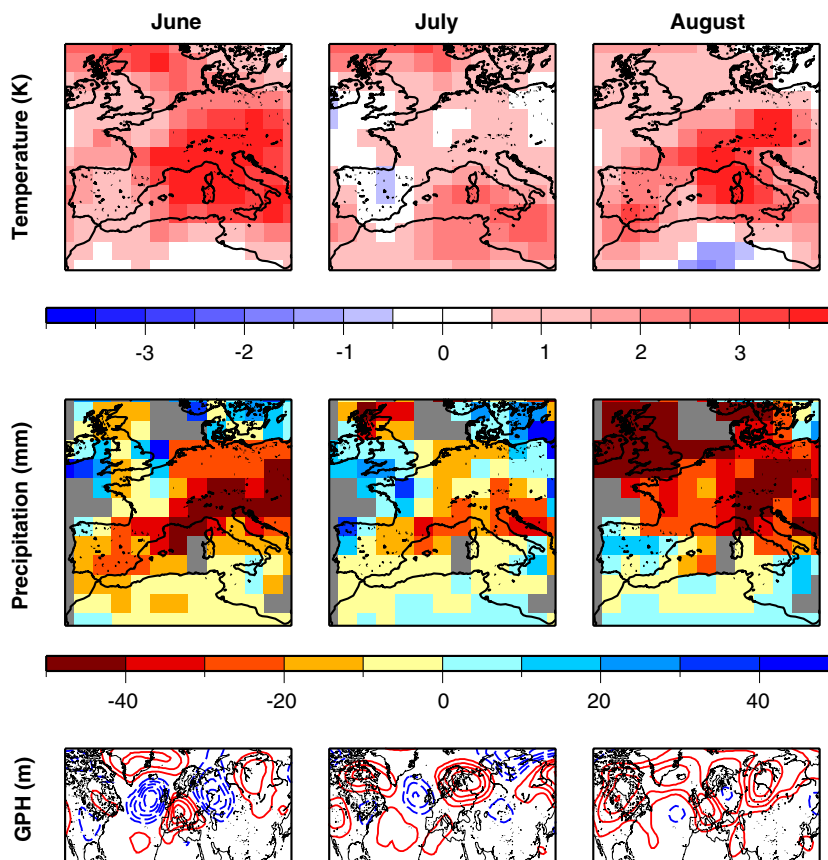
large SST anomalies in the Atlantic Ocean, Indian Ocean and Mediterranean Sea (see Fig. 2). From May to August, SST in the Mediterranean and Indian Ocean was well above average, while in the North Atlantic a bullseye pattern of cold SST surrounded by warm anomalies developed through the course of the season.

There have been several studies of the 2003 summer and of the development and predictability of European warm summers in general. Black et al. (2004) described the evolution of the event at several time and spatial scales, concluding that the anomalous temperatures were related to a combination of large scale flow anomalies, and a loss of moisture from the European land surface. It was suggested that the circulation anomalies had a dominant influence during the early part of the season, and that the drying of the land surface played a crucial role in the reinvigoration of the event during August.

The role of Atlantic Ocean conditions in European hot summers was explored in Cassou et al. (2005). This study presented evidence that diabatic heating anomalies in the tropical Atlantic Ocean, which were related to SST anomalies, played a role in the development of the hot summer. It was acknowledged, however, that

the Atlantic SST pattern alone could not explain the exceptional intensity of the 2003 event, particularly in August.

The capacity of the ECMWF forecast models to predict the August temperature anomalies was described in Grazzini et al. (2003). The short-range forecasts (less than 10 days) were successful, with both the main features of the large-scale flow and a high probability of positive 2 m temperature anomalies predicted. Forecasts with lead times of 10–30 days were also successful, with excellent skill up to 18 days. The long-range forecasts (greater than 1 month) were, however, not successful. Grazzini et al. (2003) suggested that this could be due to a combination of failure to predict the observed large SST anomalies in the Indian Ocean, and the importance of soil moisture feedback.

Several studies have addressed the extent to which the 2003 hot summer can be attributed to anthropogenic climate change, and whether summers as hot as 2003 will become commonplace in the future (Schaer et al. 2004; Beniston 2004; Stott et al. 2004). These studies all concluded that the anthropogenic global warming trend contributed to the event, and that such events are likely to become more common in the
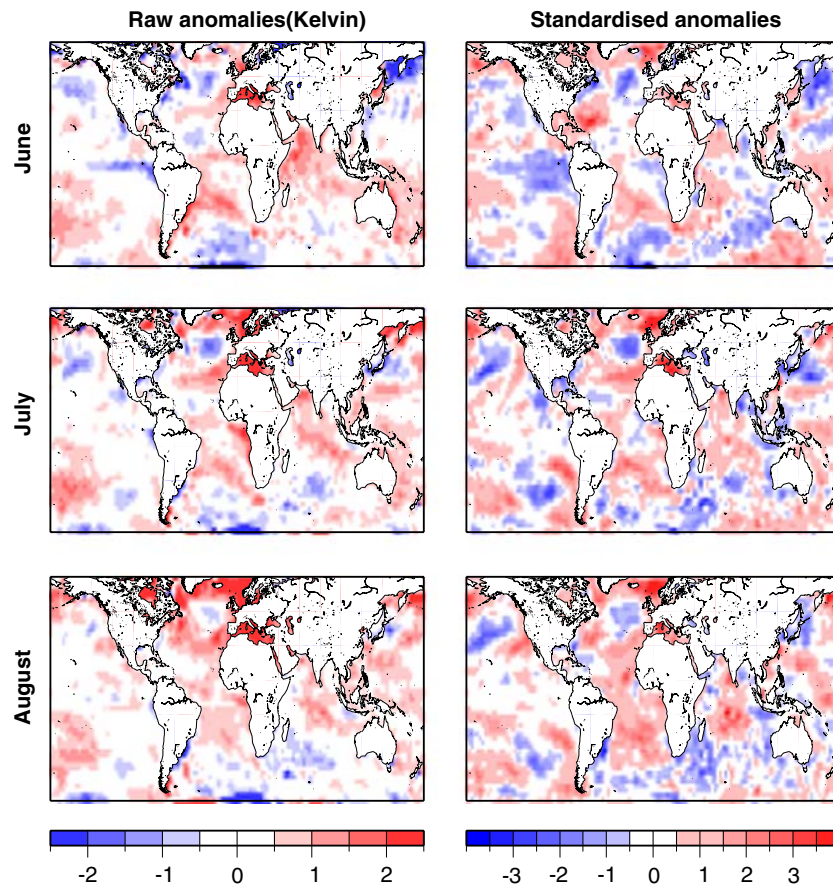
Fig. 2 Evolution of sea-surface temperature from June to August 2003. Raw anomalies are shown on the *left* and standardized anomalies are shown on the *right*. Raw anomalies are given in Kelvin and standardized anomalies are defined as the number of standard deviations from the mean

future. Indeed, Schaer et al. (2004) argued by the end of the century, summers as hot as 2003 will occur, on average, every second year.

The key question addressed by this study is: What was the influence of oceanic conditions, particularly in the Indian Ocean and Mediterranean Sea, on the development of the hot European summer of 2003? In order to tackle this, a combination of observational and model data have been used to consider the following:

1. Was the event potentially predictable (i.e. was it forced primarily by large-scale boundary forcing or was it a random atmospheric fluctuation)?
2. What were the impacts of the strong SST anomalies in the Indian Ocean and Mediterranean Sea?
3. By what mechanism did the drought and warm temperature persist into August?

Section 2 of this paper describes the data and model integrations used for the study. Section 3 uses comparison between observations and large model ensembles to ascertain how inherently predictable the

climate anomalies during 2003 were. Section 4 uses further model integrations to describe the impacts that SST anomalies in the Indian Ocean and Mediterranean Sea had on the development of the 2003 temperature anomalies. Section 5 draws on previous work to propose a mechanism by which the temperature anomalies persisted into August. Finally, Sect. 6 summarises the results of the study.

2 Data and model

The rainfall data were gridded and contoured Global Climate Observing System (GCOS) station measurements. For all other variables the NCEP/NCAR Reanalysis data were used. The reanalysis is a joint project between the National Centres for Environmental Prediction (NCEP) and the National Centre for Atmospheric Research (NCAR) to produce a multi-decadal record of global atmospheric analyses with a data assimilation system that is unchanged (Kalnay

et al. 1996). Monthly mean upper air data on standard pressure surfaces have been supplied, already gridded onto a 2.5° latitude/longitude grid. Surface and 24 h forecast fields (e.g. precipitation) are given on the equivalent T62 Gaussian grid. These reanalyses have been widely used to investigate interannual variability. Although the mean climatology is subject to uncertainties, particularly in data sparse regions such as the Indian Ocean, the interannual variability appears to be fairly robust and usable (for example Annamalai et al. 1999). All anomalies are calculated relative to the 1970–1999 climatological mean.

The model used for the integrations was HadAM3. The HadAM3 atmospheric General Circulation Model (GCM) is described in Pope et al. (2000). The standard climate version of the model, which was used in this study, has 19 vertical levels and horizontal resolution of 3.75° longitude × 2.5° latitude. For these experiments, the model was configured to call the SST field every month. This means that the model is unlikely to drift, as a coupled model might. For all the integrations, HadAM3 was forced with NCEP reanalysis SST data. This dataset was chosen because it is available up to the present day and in the past for a long enough period to form a valid climatology (1970–1999).

A series of model integrations was used to investigate the potential predictability of the anomalies that developed during the 2003 summer and the role of the Indian Ocean and Mediterranean Sea in the development of the event. Four sets of model integrations were carried out:

1. A control integration in which HadAM3 was forced with observed data for 1970–1999 (herein referred to as CONTROL).
2. A 45-member ensemble of integrations for 2003 initiated in January with observed SST everywhere on the globe (herein referred to as GLOBAL).
3. A 15-member ensemble of integrations for 2003 initiated in January with the Indian Ocean set to climatology and observed SST elsewhere (herein referred to as NOIND).
4. A 15-member ensemble of integrations for 2003 initiated in January with the Mediterranean Sea set to climatology (herein referred to as NOMED).

There are two possible ways of performing a control integration: by forcing the model with a climatological SST, or by forcing the model with observed SST and then averaging the results to derive a climatology. This study used the latter method so that the anomalies calculated by the model were comparable with observed anomalies. The CONTROL integration was performed for a 30-year period (1970–1999). A 30-year climatology was found to be sufficient to detect statistically significant results, but not so long that the results were affected by data inhomogeneities.

The ensemble was generated using a series of integrations with subtly different atmospheric starting conditions. All ensemble members were initiated on 1 January 2003. In the case of the 45-member ensemble the initial conditions were derived from 1 to 15 January 2001, 1 to 15 January 2002 and 1 to 15th January 2003. For the 15 member ensembles, the initial conditions were derived from 1 to 15 January 2003.

For all the experiments, the statistical significance of the results was assessed using a two-tailed t test. Results were considered to be significant if they passed the t test at the 95% level. The threshold of the t statistic for which data may be considered significant depends on the number of degrees of freedom, which is related to the number of ensemble members, or years within a climatology. Thus, the threshold for significance varied for the different sets of integrations, according to the number of ensemble members or the number of years in the climatology.

3 The potential predictability of the 2003 summer

The potential predictability of the 2003 summer anomalies was investigated by comparing the 45 member GLOBAL ensemble with climatologies calculated for the 30-year CONTROL integration. For each variable considered, the differences between the GLOBAL ensemble mean and the CONTROL climatology were calculated for June, July and August. The significance of the anomalies was determined using a Student's t test. In this study, the threshold for significance was 95%.

The ensemble mean anomalies for 2 m air temperature, precipitation and 500 mb geopotential height (GPH500) are shown in Fig. 3. Comparison between Figs. 3 and 1 shows that the model captures the temperature evolution of the event well. There are, however, discrepancies in the details of the structure of the anomalies—for example in July, in the model simulation, the strongest positive anomalies are over the Iberian Peninsula, while the observed anomalies over the Iberian Peninsula were weakly negative. Nevertheless, the modelled anomalies in June and August are significant at the 95% level over much of western Europe. In July, when the observed anomalies were smaller, the ensemble mean anomalies were, not surprisingly, significant over a smaller area of Europe.

Fig. 3 Ensemble mean anomalies for HadAM3 forced with observed SST for June, July and August (*left to right*). The variables in the figure are: 2 m air temperature (*top row*), precipitation (middle row) and 500 millibar geopotential height (*bottom row*). For temperature and precipitation, units and scale are given on the figure. The contour interval for geopotential height is 25 m. For temperature and precipitation, insignificant values are *grey*. For geopotential height, all values are contoured, but only significant values are *shaded*
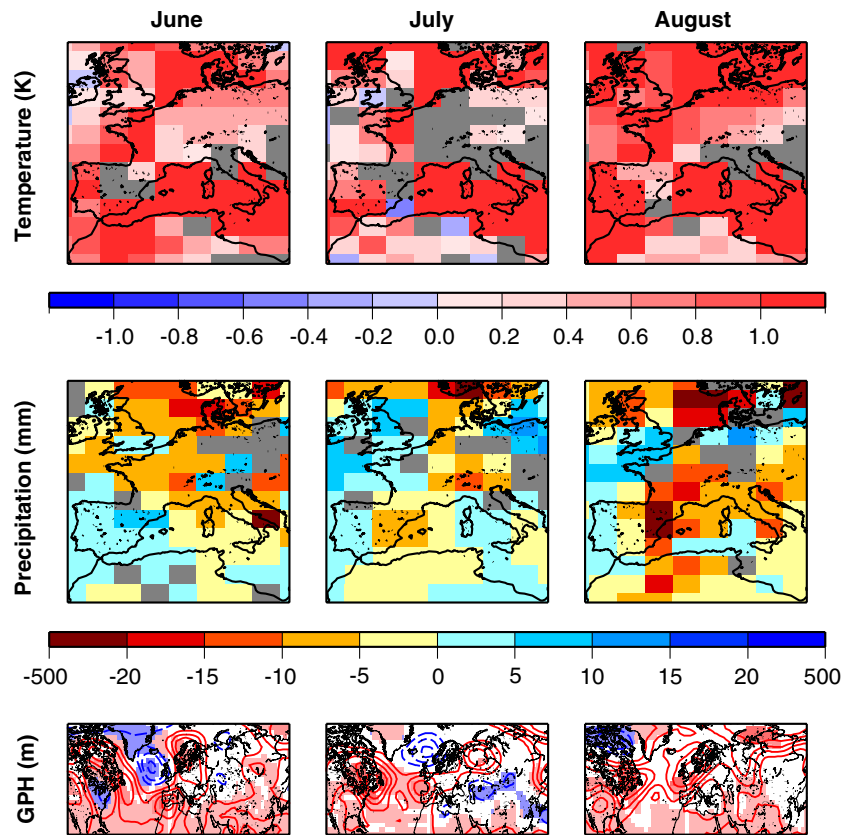
As would be expected, the magnitude of the ensemble mean anomalies is considerably smaller than that of the observed anomalies, although anomalies of a similar magnitude to those observed were generated in some ensemble members. Histograms of observed and modelled August 2 m temperature over Europe are shown in Fig. 4. Comparison between these histograms illustrates that the distribution of ensemble members for 2003 (calculated from GLOBAL) is different from the model climatology (calculated from CONTROL). Furthermore, it is evident that the observed temperature anomalies for 2003 are captured
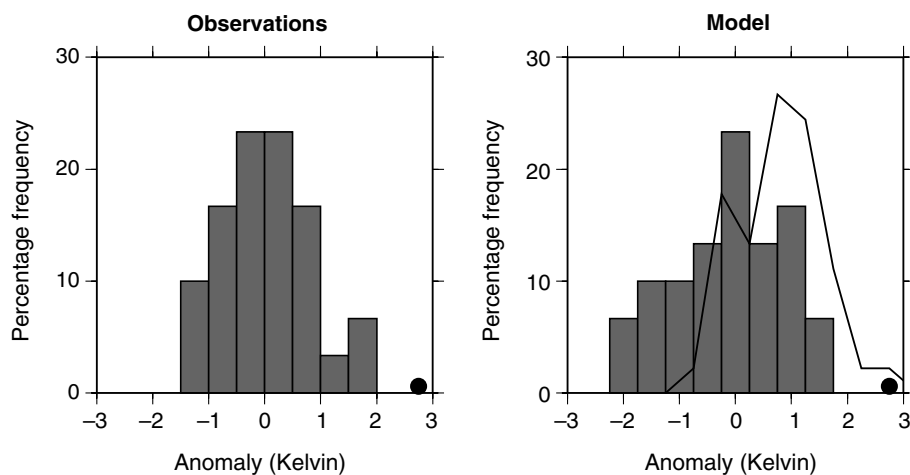

Fig. 4 Histograms of the 2 m air temperature anomalies for August over a *box* encompassing western Europe (–10/20/36/55). Only land points are included in the histogram. *Left panel* shows observed values. The *shaded histogram* gives the climatology (1970–1999) and the *dot* shows the anomaly during 2003. *Right panel* shows model values. The *shaded histogram* is the model climatology from the CONTROL integration (1970–1999); the *line histogram* is the ensemble for 2003 with HadAM3 forced with observed SST (GLOBAL integration); the *dot* shows the observed 2003 anomaly (included for comparison)

within the ensemble. The ability of the model to capture the patterns of anomalies was evaluated by plotting observed against modelled temperature anomalies for each land grid point. These plots are shown in Fig. 5. It can be seen that there is good agreement for all the months (correlation coefficients ranging from 0.53 to 0.72).

Comparison between Figs. 1 and 3 shows that the model also simulates the observed rainfall well. In particular, the simulation of the structure of the anomalies in July and August is reasonably good. In August, for example, the model captures the change from negative anomalies in the east of the study area to positive anomalies in the west. In July the positive anomalies along the western coast of continental Europe and southern Britain and the negative anomalies over central Western Europe are successfully simulated. For June, although the model correctly predicted generally low rainfall, the structure of anomalies was not captured as well as for July and August. In all months, the anomalies were significant over much of Europe for the whole season. As with the temperature, the magnitude of the precipitation

anomalies was not captured in the ensemble mean. An analogous method to that used to assess the model's prediction of temperature anomalies was used to assess the ability of the model to capture the patterns of rainfall anomalies. Observed precipitation was plotted against modelled precipitation for each land grid point where precipitation data were available. These plots are shown in Fig. 6. It can be seen that there is good agreement for all the months (correlation coefficients ranging from 0.51 to 0.75 significant at the 99% level).

In this study 500 mb geopotential height (GPH500) is used to represent the large-scale flow. Comparison between Figs. 1 and 3 shows worse agreement between the ensemble mean and observed GPH500 anomalies than was seen for the precipitation and temperature anomalies, although the observed anomalies are within the ensemble spread. In June, a geopotential low is observed over the Atlantic, with a high over western Europe and a slightly less intense low further east. The model reproduces the general pattern of a low over the Atlantic and a high over western Europe, with some areas of significance. However the eastern Europe low is further east and far smaller than that observed, and is
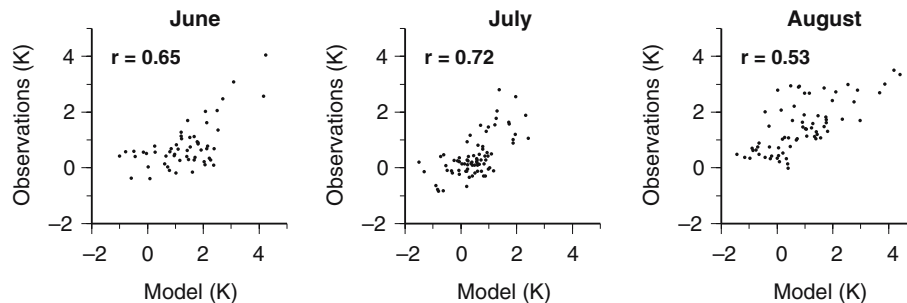

Fig. 5 Modelled (ensemble mean) temperature anomaly for HadAM3 forced with observed SST (GLOBAL integration) versus observations. The observed data are interpolated over the model grid. The graphs show ensemble mean temperature anomaly plotted against observed temperature anomaly at each grid point. The correlation coefficient, 'r' is given for each plot. June, July and August are shown (*left to right*). Only land points are plotted
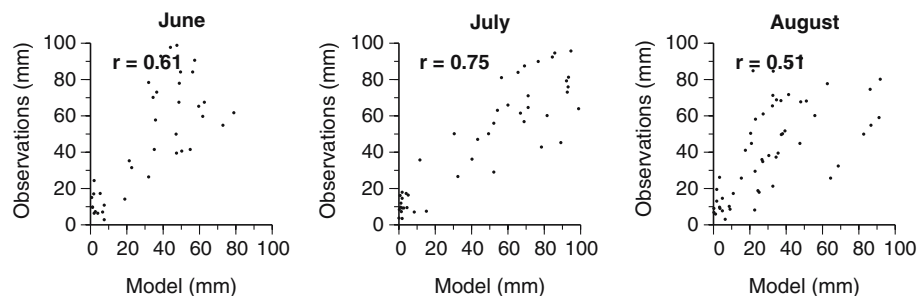

Fig. 6 Modelled (ensemble mean) precipitation for HadAM3 forced with observed SST (GLOBAL integration) versus observations. The observed data are interpolated over the model grid. The graphs show ensemble mean precipitation plotted against observed precipitation at each grid point. The correlation coefficient, 'r' is given for each plot. June, July and August are shown (*left to right*). Only land points are plotted

not significant at the 95% level. In July, a weak low was observed over the Atlantic, with a strong high in northern Europe and weak anomalies elsewhere. Again, some aspects of the general pattern of anomalies was simulated by the model. In agreement with observations, the model predicts negative anomalies in the northern Atlantic, and generally positive anomalies over the southern Atlantic and Europe. However, the locations of the maxima are incorrect and the anomalies are insignificant over most of Europe and the northern Atlantic. In August, the general pattern of observed GPH500 is positive anomalies over much of the Atlantic and Europe. The model is broadly consistent with observations in that it predicts positive anomalies over most of Europe and the Atlantic.

The previous discussion has shown that, not only the occurrence of an overall hot summer, but also the month-to-month variation in temperature and precipitation anomalies was predicted by an atmosphere-only model forced with observed SST. The fact that the broad evolution of the temperature and rainfall during the 2003 summer was captured suggests that the important aspects of the event were potentially predictable. In other words, the anomalies in 2003 were driven to some degree by the slowly varying boundary conditions.

The conclusion that the 2003 hot summer was potentially predictable is consistent with previous findings about the predictability of European climate. Colman and Davey (1999) found that it was possible to predict skilfully European summer temperature in advance of the season using a statistical model, which suggests a degree of predictability of summer temperature. Most other GCM studies (for example Palmer and Anderson 1994), have focused on the predictability of European climate during boreal spring and winter, when the influences of the NAO and ENSO are strongest. These studies found that there was some evidence of predictability in the winter. Brankovic and Palmer (2000) examined all seasons using ensembles of the ECMWF model carried out as part of the PROVOST project. It was found that there was some evidence of potential predictability of European summer climate. Interestingly, the PROVOST study found that the predictability of European climate varies considerably from year-to-year depending on the strength of remote SST anomalies (i.e. whether there was an El Nino or not). This suggests that the predictability demonstrated in the present study does not necessarily imply that European summer climate is inherently predictable every year. However, the observation that the model simulates temperature and precipitation anomalies reasonably well in the face of larger errors in

GPH500, suggests that the temperature and precipitation anomalies are sensitive to the boundary conditions imposed by the SST, as well as to the large-scale atmospheric dynamics.

It should be noted that the present study only examines potential predictability. That fact that an event is potentially predictable does not necessarily mean that it can be predicted operationally. In 2003, despite the apparent potential predictability of the positive temperature anomalies, the ECMWF seasonal forecasting system failed to forecast in May the strong temperature anomalies in JJA (Grazzini et al. 2003). The fact that the anomalies were reproduced when an atmosphere-only model was forced by observed SST suggests that the failure of the ECMWF forecast was caused by a failure to capture the SST anomalies. While the ECMWF system accurately forecast the persistence of the strong Mediterranean Sea and Atlantic Ocean SST anomalies into the summer, it failed to predict the warming in the Indian Ocean. This finding suggests that anomalous SST in the Indian Ocean may have played an important role in the development of the 2003 summer. The following section explores the roles and relative importance of the Indian Ocean and Mediterranean Sea anomalies.

4 The impacts of SST anomalies in the Mediterranean Sea and Indian Ocean

The previous section has demonstrated that the 2003 event was influenced by SST anomalies. In this section, the effect of anomalies in two regions—the Indian Ocean and the Mediterranean Sea are investigated. We are not proposing in this study that SST anomalies in the Indian Ocean and Mediterranean Sea are the sole controls on the development of the hot 2003 summer. In particular, the results reported here do not challenge the conclusion of Cassou et al. (2005), that the Atlantic played an important role. Nevertheless, there are several reasons for studying the impact of the Indian Ocean and Mediterranean Sea. Firstly, Fig. 2 shows that during the summer of 2003 there were large SST anomalies in both the Indian Ocean and the Mediterranean Sea. Secondly, as was described earlier, the Grazzini et al. (2003) review of the ECMWF forecast of the 2003 anomalies suggests that Indian Ocean anomalies affected the surface air temperature over Europe during the 2003 summer. Thirdly, the traditional explanation of the observed association between Mediterranean Sea SST and large-scale atmospheric circulation patterns is that the atmosphere influences the Mediterranean, and the Mediterranean is effec-

tively passive (for example Xoplaki et al. 2003). The extreme anomalies in the Mediterranean experienced during 2003 provided an ideal opportunity to test this hypothesis.

The effect of the observed SST anomalies was investigated by comparing the NOIND and NOMED integrations with the GLOBAL integrations. The impact of the anomalies in the Indian Ocean or Mediterranean Sea on a given field was assumed to be GLOBAL-NOIND or GLOBAL-NOMED respectively. The results are shown in Figs. 7, 8 and 9. Table 1 gives the spatially averaged ratio between these ensemble means, which may be considered a semi-quantitative measure of the contribution of the Indian Ocean and Mediterranean Sea SST anomalies to the European temperature and precipitation anomalies simulated by the model.

In June, Fig. 2 shows that in 2003 the Mediterranean Sea was approximately 1.5 K warmer than usual. The Indian Ocean was also up to 1.5 K warmer, with the strongest anomalies in the west. Figure 7 shows that, in the model, both the Indian Ocean and Mediterranean Sea SST significantly affect the temperature and precipitation over Europe. The anomalous SST of the Indian Ocean has the effect of decreasing the temperature over much of Europe (with the exception of southernmost areas). In addition, the model results imply that the Indian Ocean contributed to a decrease in rainfall over southern Europe, and small, but significantly positive rainfall anomalies over northern parts of continental Europe and the UK. In contrast to the Indian Ocean, the warming in the Mediterranean Sea causes significant positive temperature anomaly over the whole of Europe, except for the southern tip
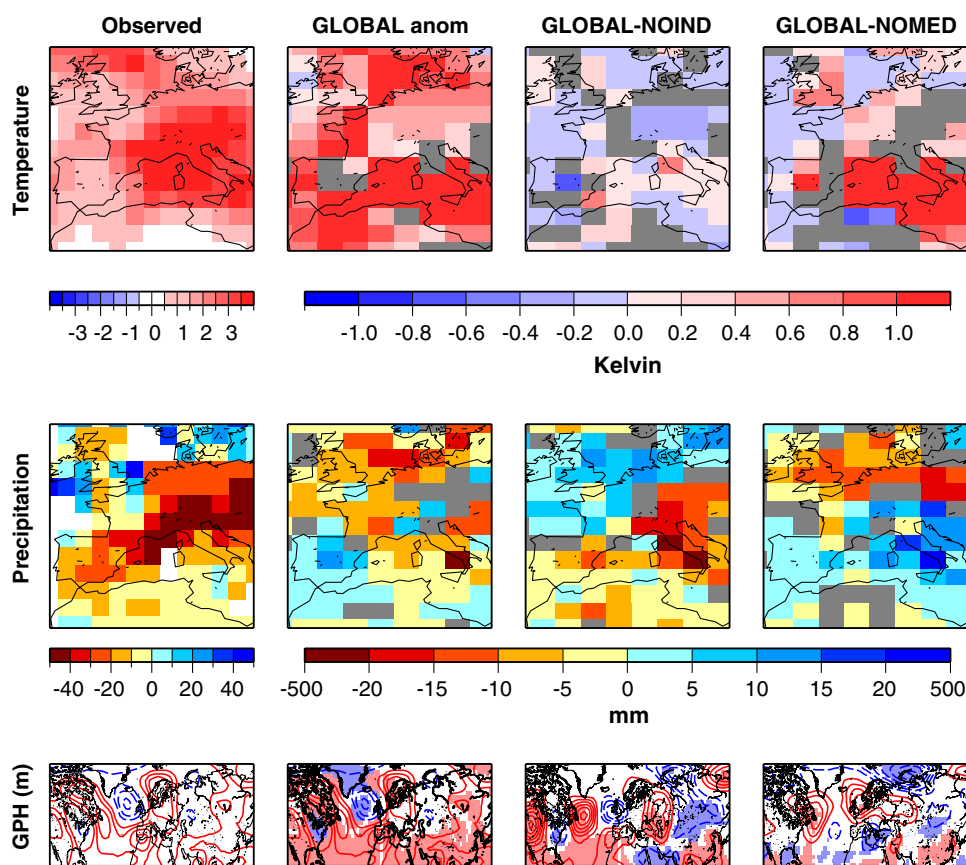

Fig. 7 Ensemble mean 2 m air temperature, precipitation and 500 mb Geopotential Height for June 2003. *From left to right* the *first panel* shows the observed anomalies, the *second panel* shows ensemble mean anomalies when HadAM3 is forced with global observed SST (GLOBAL), the *third panel* shows the difference between the GLOBAL integration ensemble mean and the NOIND ensemble mean (HadAM3 forced with global observed SST everywhere apart from the Indian Ocean, which is set to climatology); the *fourth panel* shows the difference between the GLOBAL integration ensemble mean and the NOMED integration ensemble mean (HadAM3 forced with global observed SST everywhere apart from the Mediterranean Sea, which is set to climatology). *From top to bottom* the *top panel* shows 2 m air temperature anomaly in Kelvin; the *middle row* shows total precipitation anomaly in mm and the *bottom panel* shows 500 mb geopotential height (contour interval 25 m). For temperature and precipitation, insignificant values are *greyed out*. For geopotential height, all values are contoured, but only the significant values are shaded. The contour interval is 25 m
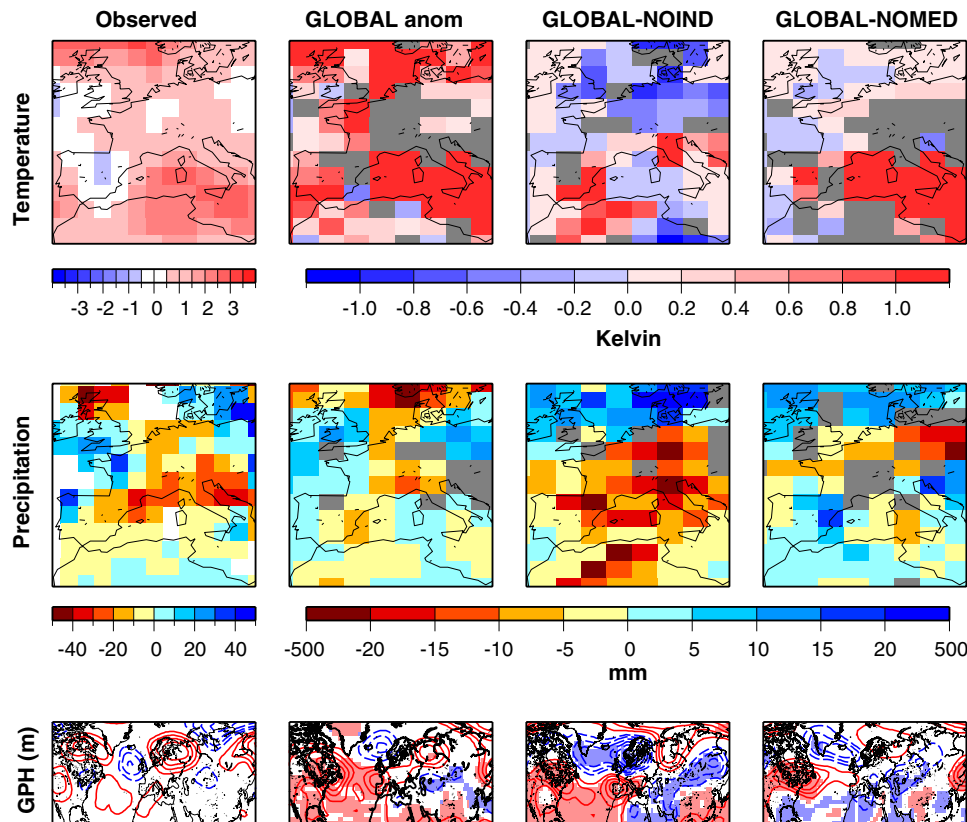
Fig. 8 Ensemble mean 2 m air temperature, precipitation and 500 mb Geopotential Height for July 2003. *From left to right* the *first panel* shows the observed anomalies, the *second panel* shows ensemble mean anomalies when HadAM3 is forced with global observed SST (GLOBAL), the *third panel* shows the difference between the GLOBAL integration ensemble mean and the NOIND ensemble mean (HadAM3 forced with global observed SST everywhere apart from the Indian Ocean, which is set to climatology); the *fourth panel* shows the difference between the GLOBAL integration ensemble mean and the NOMED inte-gration ensemble mean (HadAM3 forced with global observed SST everywhere apart from the Mediterranean Sea, which is set to climatology). *From top to bottom* the *top panel* shows 2 m air temperature anomaly in Kelvin; the *middle row* shows total precipitation anomaly in mm and the *bottom panel* shows 500 mb geopotential height (contour interval 25 m). For temperature and precipitation, insignificant values are *greyed out*. For geopotential height, all values are contoured, but only the significant values are *shaded*. The contour interval is 25 m

of the Iberian Peninsula. Furthermore, the Mediterra-nean warming leads to enhanced rainfall over southern Europe and deficient rainfall over northern regions including the UK. In the model, the Mediterranean anomalies appear to contribute to a low GPH500 over southern continental Europe and the Mediterranean. The Indian Ocean, in contrast, contributes to high GPH500 over southwestern Europe and low GPH500 over the northeastern Atlantic.

In July, Fig. 2 shows that the Mediterranean SST anomalies were stronger in July than June, exceeding 2 K everywhere. The Indian Ocean also continued to be generally warm. Again, Fig. 8 shows that, in the model, both Indian Ocean and Mediterranean Sea SST have a significant impact on temperature and rainfall over much of continental Europe. The Indian Ocean anomalies are associated with a reduction in the tem-perature over northern continental Europe and an in-crease the temperature over southern Europe. The Mediterranean anomalies are associated with warming over much of western Europe—particularly the south, although in eastern parts of the study area, there is no significant influence. The model results also imply that the Indian Ocean influences the precipitation signifi-cantly throughout continental Europe—apparently making a strong contribution to the observed rainfall deficit. The Mediterranean influence on precipitation is weaker and only significant in northern and southern-most continental western Europe. In the model, the Indian Ocean has a strong effect on GPH500, con-tributing to a high over southwestern continental Europe and a low over northwestern continental Europe. Over the Mediterranean, the Indian Ocean and Mediterranean Sea have competing influences,
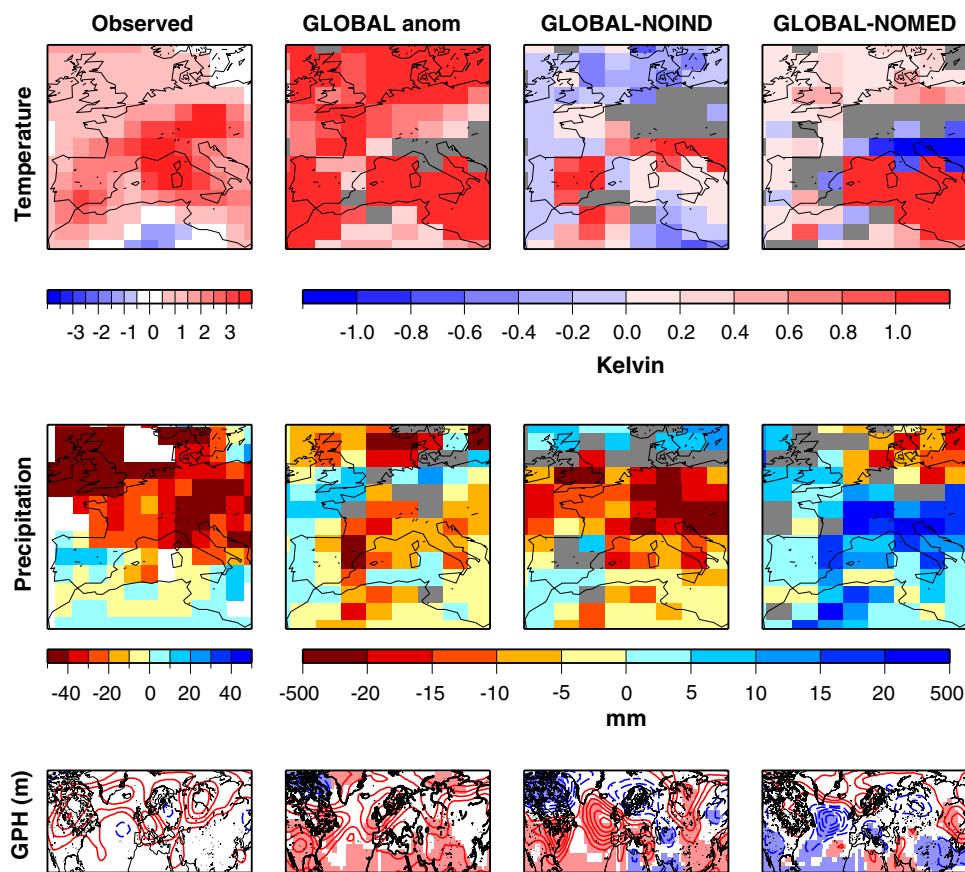
Fig. 9 Ensemble mean 2 m air temperature, precipitation and 500 mb Geopotential Height for August 2003. *From left to right* the *first panel* shows the observed anomalies, the *second panel* shows ensemble mean anomalies when HadAM3 is forced with global observed SST (GLOBAL), the *third panel* shows the difference between the GLOBAL integration ensemble mean and the NOIND ensemble mean (HadAM3 forced with global observed SST everywhere apart from the Indian Ocean, which is set to climatology); the *fourth panel* shows the difference between the GLOBAL integration ensemble mean and the NOMED integration ensemble mean (HadAM3 forced with global observed SST everywhere apart from the Mediterranean Sea, which is set to climatology). *From top to bottom* the *top panel* shows 2 m air temperature anomaly in Kelvin; the middle row shows total precipitation anomaly in mm and the *bottom panel* shows 500 mb geopotential height (contour interval 25 m). For temperature and precipitation, insignificant values are greyed out. For geopotential height, all values are contoured, but only the significant values are shaded. The contour interval is 25 m

with the Mediterranean anomalies creating a tendency to low GPH500 and the Indian Ocean anomalies creating a tendency to high GPH500.

Table 1 Ratio between GLOBAL-NOMED and GLOBAL-NOIND to GLOBAL 2 m temperature and precipitation anomalies for a box encompassing western Europe (–10/20/36/55 land points only)

	NOMED	NOIND
June		
2 m temperature	0.36	–0.07
Precipitation	0.49	–0.33
July		
2 m temperature	0.57	–0.48
Precipitation	–1.10	2.22
August		
2 m temperature	-0.08	0.91
Precipitation	–1.21	0.47

In August, both the Mediterranean Sea and Indian Ocean remained anomalously warm. Both the Indian Ocean and the Mediterranean Sea had significant impacts on temperature and rainfall. Figure 9 suggests that, in the model, the Mediterranean warming favoured enhanced rainfall over the whole region of interest and significantly lower surface air temperatures over parts of southern Europe. The Indian Ocean anomalies, in contrast, favoured low rainfall over most of continental Europe and strong warming over western continental Europe, somewhat as in June and July. The Mediterranean and Indian Ocean had opposing impacts on the GPH500 pattern. The Indian Ocean anomalies were associated with a strong blocking high centred over northwest Europe, while the Mediterranean anomalies were associated with a low.

It is evident from Figs. 7, 8 and 9 that throughout the season, the Mediterranean Sea and Indian Ocean had competing effects on GPH500 over the Mediterranean Sea. Moreover, throughout the season the ratio between the spatially averaged GLOBAL and GLOBAL-NOIND precipitation and temperature anomalies had opposite polarity to the ratio between GLOBAL and GLOBAL-NOMED (see Table 1). This suggests that the Indian Ocean anomalies and Mediterranean Sea anomalies also had competing effects on the development of the 2003 precipitation and temperature anomalies. This is particularly clear for precipitation, and temperature in July. In June, the spatially averaged ratio between GLOBAL and GLOBAL-NOIND was low, and the same is true for GLOBAL-NOMED in August, although Figs. 7, 8 and 9 show that both the Indian Ocean and Mediterranean Sea had significant impact over some parts of Europe for the whole season.

In summary, comparison between model integrations with global observed SST and model integrations with SST in the Mediterranean Sea and Indian Ocean set to climatology suggests that conditions in both the Indian Ocean and Mediterranean Sea contributed to the development of the 2003 positive temperature anomalies. The warming in the Mediterranean caused GPH500 to be anomalously low over the Mediterranean and southern Europe throughout the season. In June and July, this favoured markedly high temperatures and low rainfall in northern Europe and weakly positive rainfall anomalies and some areas of positive temperature anomalies in the south. This pattern in temperatures and rainfall was most likely caused by an increased tendency to convection over the Mediterranean and associated subsidence, with consequent lack of convection and clear skies in northern Europe. In August, the pattern was different, with the warming in the Mediterranean associated with low GPH500, extra convection and hence strongly positive rainfall anomalies throughout Europe. In contrast to the Mediterranean, the Indian Ocean SST anomalies created a tendency towards a geopotential high over the Mediterranean, which spread further north as the season progressed. In the early part of the season, this resulted in subsidence and low rainfall in southern Europe, and convection and high rainfall in northern Europe. In July, the Indian Ocean warming caused high pressure and low rainfall in southern continental Europe. This effect intensified in August, during which the Indian Ocean conditions were associated with low rainfall throughout Europe, and markedly high temperatures throughout the western and southern parts of the continent.

5 Why the event persisted into August

By August, the model results suggest that warming in the Mediterranean Sea favours enhanced rainfall and a waning of the positive temperature anomalies in parts of Europe. These tendencies are counteracted by the Indian Ocean SST anomalies, which inhibit the convection and rainfall induced by the warming in the Mediterranean, allowing the positive temperature anomalies to persist into August. The following discussion proposes a mechanism by which this might happen.

The idea that the anomalies in the Indian Ocean region can affect European climate is not new. Rodwell and Hoskins (1996) described the impact of the Asian summer monsoon on the mean climate over the Mediterranean. They demonstrated that descent associated with the Rossby wave response to the monsoon contributed to the climatologically dry summer over the Mediterranean. The central issue addressed by the Rodwell and Hoskins study was the development of mid-latitude deserts such as the Sahara. However, one of their findings—that heating in the Indian monsoon region causes anomalous descent over the Mediterranean, is relevant to the current study.

The starting point of the Rodwell and Hoskins (1996) study is the results of Gill (1980). Gill (1980) showed that when monsoon heating is imposed, a region of weak descent develops to the west of the heating, associated with a Rossby-wave disturbance. Rodwell and Hoskins (1996) used an idealised model to determine whether this descent could explain the existence and location of the Sahara desert, and the dryness of the eastern Mediterranean in summer. Two sets of integrations were performed. In the first set, a simple elliptical heating was centred about 90°E and 10°N. In the second set of integrations, the heating centre is shifted northwards to 25°N, mimicking the monsoon onset. The results of these experiments demonstrated that monsoon heating does indeed induce a region of descent to the west, which is enhanced by interaction with the mid-latitude westerlies. Rodwell and Hoskins (1996) argued that this mechanism explained both the dryness of the Mediterranean in the summer months, and the existence of the Sahara desert.

This leads to the question of whether this mechanism can explain the impact of anomalous heating in the Indian Ocean on precipitation over the Mediterranean. Figure 10 compares 500 mb vertical wind (omega) anomalies induced by August 2003 Indian Ocean SST anomalies (Fig. 10b) with those resulting from the Rodwell and Hoskins imposed heating

(Fig. 10a). The broad similarity of the results is clear. In both cases, there is ascent over the Indian Ocean and equatorial Africa, and descent over north Africa and the Mediterranean. Figure 11b shows that, in the model, warming in the Indian Ocean causes enhanced precipitation in western India as well as within the Indian Ocean, producing an additional heat source of the type imposed in the Rodwell and Hoskins (1996) study, although the location is different. This supports the hypothesis that, in HadAM3, warming in the Indian Ocean leads to descent over the Mediterranean, by the mechanism demonstrated in Rodwell and Hoskins (1996). Although only August is considered here, the descent over the Mediterranean, and low rainfall over the Mediterranean and southernmost Europe, is observed for all three months analysed (see Figs. 7, 8, 9—500 mb omega not shown).

The question remains of whether these events in HadAM3 occurred in the real world. It was observed that even though the total all India rainfall during the 2003 monsoon was normal, in July there were substantial positive rainfall anomalies over much of India. By August, these were replaced by negative anomalies (Fig. 11a). Throughout the season, there was anomalous descent over Europe, and ascent over northern tropical Africa (Fig. 11c, only August shown). The fact that the monsoon was weak in August, when the rainfall anomalies in Europe were strongly negative may reflect a delay in the remote response of the Mediterranean climate to the remote forcing over the Indian monsoon region, Alternatively, heating in the Indian Ocean region other than on the Indian mainland might induce the Rossby wave response described above and by Rodwell and Hoskins. Because the anomalous vertical wind response over the Mediterranean was observed for all three months, despite variation in the strength of the monsoon, this latter hypothesis would seem more likely.

Fig. 10 500 mb omega for August 2003 (contour interval 0.05 m/s). **a** Rodwell and Hoskins simulation for an idealized model with a heat source placed on the Indian subcontinent. **b** Difference between GLOBAL and NOIND
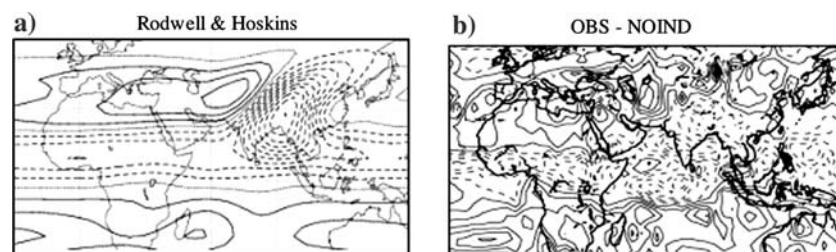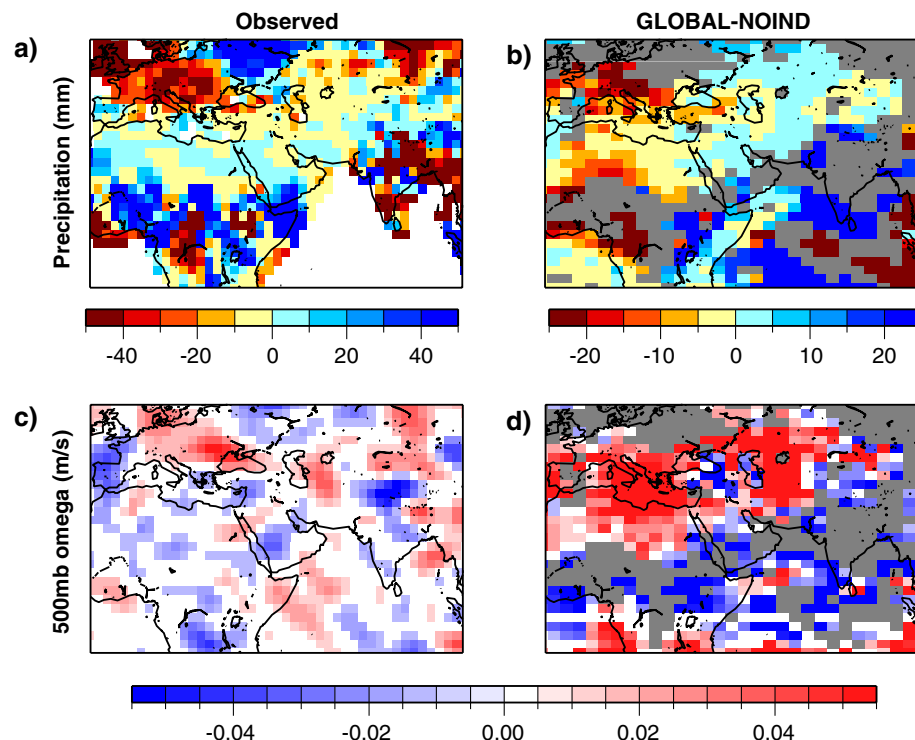

Fig. 11 a Observed precipitation anomalies **b** GLOBAL-NOIND precipitation anomalies **c** Observed 500 mb omega anomalies **d** GLOBAL-NOIND 500 mb omega anomalies. For the model integrations, not significant values are *greyed out*

It is evident from Fig. 11d that although the descent induced by the Indian Ocean anomalies is focused over the Mediterranean, the associated precipitation anomalies are more widespread, covering much of central Europe (see Fig. 11b). This is not surprising. The suppression of convection over the Mediterranean, caused by the anomalous descent would be expected to cause reduced rainfall over the surrounding continent. This is because the warm Mediterranean would normally act as a source of moisture for Europe, and if convection is suppressed, this would not be possible. Thus, the observation that the location of the anomalous descent is not consistent with the location of the largest rainfall anomalies does not invalidate the hypothesis.

In summary therefore, in normal circumstances, a hot event in Europe would enhance warming in the Mediterranean, eventually causing increased evaporation and convection. The cloudy skies would then result in less radiative heating and a cessation of the hot weather—effectively a negative feedback. In this case however, we propose that the heating in the Indian Ocean region induced a Rossby wave response, which favoured descent over the Mediterranean. This suppressed convection, interfered with the negative feedback loop described above and caused the temperature anomalies to persist into August.

6 Conclusions

The key question addressed by this study was: what was the influence of oceanic conditions on the development of the hot European summer of 2003? This problem was addressed using large ensembles of atmosphere-only model integrations. Integrations forced with observed SST suggested that oceanic conditions did indeed contribute to the development of the positive temperature anomalies during 2003, and that the warm and dry anomalies were therefore potentially predictable. Further integrations with the Indian Ocean and Mediterranean Sea set to climatology demonstrated that the origin of this potential predictability is, at least in part, the anomalous conditions in the Indian Ocean and Mediterranean Sea. Comparison with previous work suggested a dynamic mechanism by which the event was prolonged into August. The main conclusions of this study can be summarised as follows:

1. When forced with observed SST, HadAM3 replicates the observed surface temperature and precipitation, suggesting that the 2003 warm anomalies and drought were potentially predictable.

2. Both the Indian Ocean and Mediterranean Sea had a significant influence on temperature and precipitation throughout the summer with the Mediterranean contributing most strongly to the early part of the event and the Indian Ocean contributing most strongly to the anomalous temperatures during August.

3. Previous work has suggested that the Mediterranean Sea responds to atmospheric circulation, but does not contribute to it. This study challenges this suggesting instead that Mediterranean SST anomalies have a significant influence on the large-scale atmospheric circulation.

4. Throughout the season, the Indian Ocean warming caused descent over the Mediterranean, inhibiting convection over the Mediterranean and southern Europe. In August, this led to a prolonging of the temperature anomalies by inhibiting convection over the excessively warm Mediterranean.

5. A mechanism by which a Rossby wave response to heating in the Indian Ocean region causes descent to the west has been proposed.

This study has implications both for the development of operational seasonal forecasting systems for Europe and for further work on European climate variability. Previous work has suggested that the Mediterranean Sea responds passively to the large-scale atmospheric circulation. This study has challenged this view, suggesting instead that processes in the Mediterranean may play an important role in the development of climate anomalies over Europe. Further work, using coupled models should test this hypothesis and describe more fully the feedback between Mediterranean processes and large-scale climate over Europe.

The potential influence of the Indian monsoon on the European summer climate was explored in Rodwell and Hoskins (1996). This study has extended this idea, suggesting that interannual variability in Indian Ocean conditions may modulate the summer climate of Europe. Further work, using idealised models and observations, should test this hypothesis and address outstanding problems such as: are the locations of heating anomalies in the Indian Ocean basin critical? What role do diabatic heating anomalies caused by active-break cycles in the monsoon play in modulating European climate?

It has been shown that events such as the summer of 2003 are potentially predictable, raising the possibility that, in the future, operational forecasting systems may be able to predict such hot summers. However, it has also been shown that in order for this to happen, Indian

Ocean SST needs to be predicted correctly. Currently, simulation of Indian Ocean dynamics is regarded as an extremely tough challenge for coupled models (see Spencer et al. 2005). Resolving the problems that coupled models have in simulating Indian Ocean processes is therefore crucial for developing successful seasonal forecasting systems for Europe.

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