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Influence of sea surface temperature on the European heat wave of 2003 summer. Part II: a modeling study

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Abstract The Center for Ocean–Land–Atmosphere Studies Atmospheric General Circulation Model is used to investigate the role of global boundary conditions of sea surface temperature (SST) in the establishment and maintenance of the European heat wave of 2003 summer. It is found that the global SST anomalies can explain many major features of the European heat wave during the summer of 2003. A further experiment has investigated the role of SST outside the Mediterranean area. This supplements the results of a previous study where the role of warm Mediterranean SST was analyzed. The results suggest that the SST anomalies had an additional effect of reducing the baroclinicity in the European area reinforcing the blocking circulation and helping to create ideal conditions for the establishment of the heat wave.

Keywords Heat wave · Extreme · 2003 Summer · Europe · SST influence · Mediterranean · AGCM experiment

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1 Introduction

The heat wave affecting Europe during summer of 2003 is considered one of the major climate anomalies in the extratropics in the recent times. The central-western Europe was the area most affected by high temperature, in particular France, Italy and Britain. The main features that characterized this event are described, analyzed and discussed in detail in the study by Feudale and Shukla (2010) (hereafter referred to as FS10a). FS10a concluded that, even if the main atmospheric circulation during that event was favorable to a blocking situation, blocking alone is not sufficient to explain such a large amplitude and duration. Therefore, in addition to some favorable synoptic conditions (Cassou et al. 2005), the very low level of soil moisture and the strong SST anomalies, especially in the Mediterranean Sea, may significantly contribute to enhance the heat waves occurring in this area. Focusing on just the SST as forcing, based on the analysis of data alone it is not possible to investigate whether the large Mediterranean SST anomalies can, in turn, affect the land surface temperature and atmospheric circulation in the Mediterranean area. Several atmospheric GCM sensitivity studies have been carried out to investigate this question. Black and Sutton (2007), using HadAM3 model, found that the Mediterranean SST anomalies had significant effect on the heat wave. In contrast, Jung et al. (2006) using 3-month long summer integrations of the ECMWF model found that the Mediterranean SST had almost no effect on the circulation and land surface temperature over the European area. Feudale and Shukla (2007), using 9-month integrations of the COLA model, found that the Mediterranean SST alone produced nearly all the major features of the 2003 heat wave (anomalous anticyclonic circulation, warmer land surface temperature, etc.) but with reduced intensity.

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The three numerical experimental studies described above used three different models and quite different experimental designs including the length of the integrations. For example, Jung et al. (2006) only made 3-month integrations whereas Feudale and Shukla (2007) made 9-month integrations. The COLA model used by Feudale and Shukla (2007) had the unrealistic feature of producing convection over very warm Mediterranean SST which was not observed.

To give a complete view of possible SST forcings beside the Mediterranean Sea (Feudale and Shukla 2007), in this paper the primary goal is to investigate if the global boundary conditions of SST can explain the amplitude and the persistence of this exceptional heat wave of 2003. It is well understood that, irrespective of the external anthropogenic forcings, an observed seasonal mean anomaly of atmosphere circulation should be explained by the cuncurrent forcing from the global boundary conditions. Whether the global anomalies of SST and soil moisture were caused by natural fluctuations generated by interactions among the coupled ocean–land–atmosphere system or due to anthropogenic forcing is beyond the scope of this paper. Therefore, the authors do not investigate whether this heat wave was a manifestation of global warming.

In this study, the Center for Ocean–Land–Atmosphere Studies (COLA) Amospheric General Circulation Model (AGCM) is integrated with and without the global observed SST anomalies (SSTAs) for 2003. The role of global SST anomalies in the occurrence of the 2003 heat wave has been investigated by analyzing the differences between the two integrations. It is found that COLA model forced by global SST anomalies can explain many major features of the 2003 heat wave. The possible role of the Mediterranean SST anomalies, which were exceptionally high during 2003, has been investigated in a previous study (Feudale and Shukla 2007) which found that the Mediterranean SST anomalies had a demonstrable role in further enhancing the 2003 heat wave. As already mentioned above, this result is quite different from some previous studies which showed no influence of the Mediterranean SST anomalies. Different conclusions from different AGCMs suggest that, even for the simulation of one of the largest regional climate anomalies over Europe, the results remain highly model-dependent. The influence of the sea temperature outside the Mediterranean is also tested with another sensitivity experiment, also indicating a possible positive contribution from the northern part of the Atlantic Ocean and the North Sea and Baltic Sea.

The authors have not investigated the possible role of soil moisture anomalies in the initial conditions in further enhancing the intensity and persistence of the heat wave. However, based on several studies in the past, it is quite reasonable to conjecture that dry soil caused by reduced rainfall contributed to the amplification of the heat wave. Fennessy and Kinter (2009), which used a similar version of the COLA AGCM, ran some experiments evaluating the sensitivity of initial soil wetness and concluded that the dry local soil were important in forcing that event. Since SST anomalies alone are able to explain a substantial part of the heat wave, the combined effects of SST anomalies and land surface anomalies should be able to explain nearly all the major features of the 2003 heat wave.

This paper is organized as follows. Sect. 2 describes the data and the AGCM used in the study. Sect. 3 describes the AGCM results for global SST anomalies while Sect. 4 provides an analysis of SST anomalies outside the Mediterranean area. Sect. 5 summarizes the model results and gives main conclusions.

2 Model, data and model validation

The COLA AGCM version V2.2.7 is used for investigating the influence of SST on the heat wave. The COLA AGCM includes the NCAR CCM3 dynamics with triangular truncation at 63 wave numbers (T63), 18 unevenly spaced sigma layers, Relaxed Arakawa–Schubert convection, and the Simplified Simple Biosphere Model (SSiB; Xue et al. 1991) . The land surface is represented by a modified version of the SSiB that is described by Dirmeyer and Zeng (1999). The documentation of the model is given by Kinter et al. (1997). Ten ensemble members are performed for each experiment. In order to isolate the SST effect from the atmospheric initial conditions effect, the simulations are initialized on 1 January and run up to the end of September. The model is initialized with global atmospheric and surface National Centers for Environmental Predictions–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis at 2.5° horizontal resolution (Kalnay et al. 1996; Kistler et al. 2001) for the dynamical parameters and Global Offline Land-surface Dataset (GOLD) Climatological Soil Wetness (Dirmeyer and Tan 2001) for the soil moisture. The CO_2 loading is set to 345 ppm. The SST is updated daily during the whole period with the global OISST (Reynolds et al. 2002). Since the heat wave affected a large part of Europe (more than 2.25×10^6 km^2), the resolution of this GCM is adequate to address the scale of the heat wave.

Different datasets are used for model validation: monthly station data of the Climatic Research Unit (CRU, Mitchell and Jones 2005) provides the longest continuous timeseries for validation for surface temperature and precipitation; the gridded surface maximum temperature data (T_{max}) is also used and is provided by Pingping Xie from NCEP (personal communication). This dataset consists of a global, daily surface temperature on a 0.5° grid, available from 1 October 1977 to the present.

To verify the performances of the model in the European area during the summer season from June to August

(JJA), a 20-year climatology (1982–2001) of surface temperature and precipitation was calculated using a long run of the AGCM and compared with CRU data. Despite the coarse model resolution with respect CRU data, the AGCM is able to reproduce the spatial distribution of surface temperature quite well including also the typical climate of the Alps region (Fig. 1a, b). For the precipitation, the model distribution looks reasonable except for eastern Europe where it shows an overestimation of rainfall (Fig. 1c, d). Also the study by Fennessy and Kinter (2009) tested the model preformance in this area for other seasons and it resulted to have a reasonable climatological near surface temperature and precipitation patterns and a reasonable seasonal cycle (Fennessy and Kinter 2009).

3 AGCM experiments for global SST anomalies

In the first set of experiments the role of global SST is analyzed. In the first simulation referred as OBS.SST, the model is forced with global daily observed OISST from 1 January to 30 September. All the results displayed here are ensemble means. In order to assess the model ability to reproduce the European heat wave during summer (JJA) of 2003, the simulated anomalies are compared with the observed anomalies. For this reason, a control integration (referred as CLIM.SST) from 1 January to 30 September imposing global daily climatological SST as boundary conditions has been carried out. A list of all the experiments and their characteristics is presented in Table 1. The difference between the JJA OBS.SST ensemble mean and the JJA CLIM.SST ensemble mean is calculated for each variable and compared with the observed anomalies. For temperature, the result of T'_{max} (Fig. 2a) is compared with the observed T'_{max} from the Xie dataset shown in Fig. 1b of FS10a. The spatial structure of the anomaly is well simulated, extending to the entire western and central Europe. The local maximum in the south-western France, close to Switzerland, is also well simulated. Even though the spatial structure looks similar, the simulated intensity is weaker by

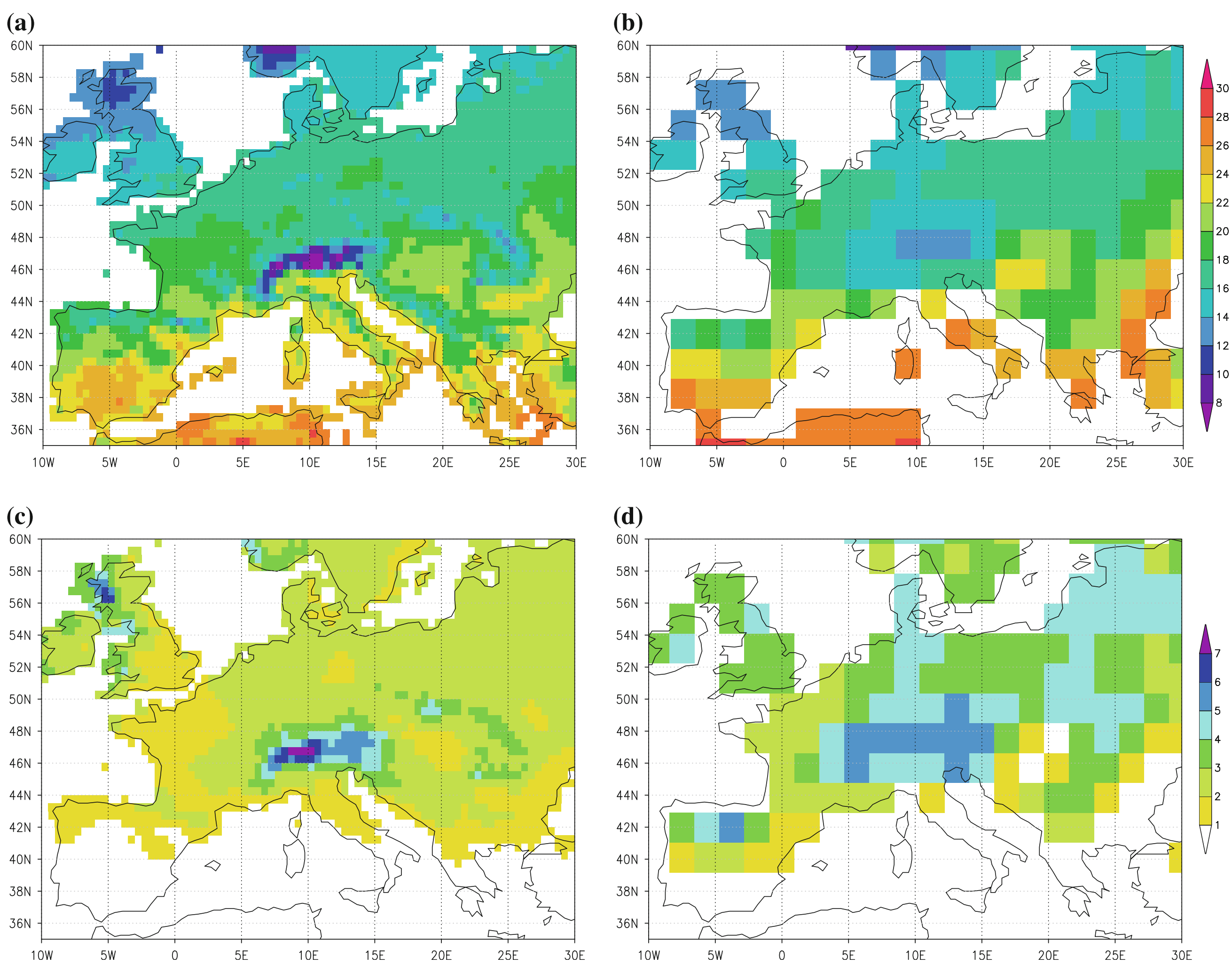


Fig. 1 JJA 1982–2001 surface temperature mean for **a** CRU data and **b** COLA AGCM. In **c** and **d** the same only for precipitation

Table 1 List of experiments performed with the COLA AGCM

EXP	IC	LEN	BC (SST)	# ENS.
CLIM.SST	00Z01Jan03	9 mo	daily climatological OISST-V2	10
OBS.SST	00Z01Jan03	9 mo	daily 2003 OISST-V2	10
OBS.MED	00Z01Jan03	9 mo	daily (MedBl 2003+rest clim) OISST-V2	10
CLIM.MED	00Z01Jan03	9 mo	daily (MedBl clim+rest 2003) OISST-V2	10

From the first to the fifth column the experiment code, the date of initial conditions, the length of the run, the boundary conditions and the number of ensemble members are listed respectively. “MedBl” stands for “Mediterranean Sea and Black Sea”

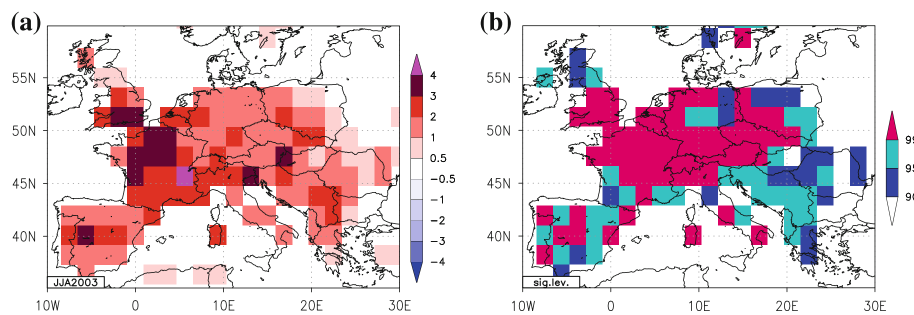


Fig. 2 **a** JJA T'_{max} from the COLA AGCM simulation of the heat wave of 2003 summer (°C); **b** map of the areas where the result in **a** is significant at more than 90% significance level

about 2–3°C everywhere compared to observations. Figure 2b shows that the result is statistically significant above the 90% level in almost the entire area affected by the heat wave.

For the same area (1°W–10°E, 43°N–50°N) as in Fig. 1c of FS10a, the time series of the area-averaged simulated anomalies are shown with a 7-day running mean in Fig. 3 (solid line). Although the amplitude is nearly half of the observed, the evolution of the simulated heat wave is remarkably similar. The observed temperature anomaly becomes positive after the month of June, and then, after a break in July, it increases again in August when, during the middle of the month, it reaches its maximum of 5°C, about half of the observed maximum amplitude. In the simulated event, the positive anomaly persists until the end of September, but, in the observations, the temperature gets closer to the climatology by the beginning of September. Therefore, the simulated anomaly starts later and ends later.

The fields of z500, precipitation and soil moisture are also compared with the analysis results in FS10a. From reanalysis, the z500 field during the 2003 JJA summer season (shown in Fig. 4 of FS10a) shows the typical blocking “Ω -pattern” characterizing the extremely hot episodes (Colacino and Conte 1995). The positive z500 anomaly centered over Europe reaches a maximum of about 40–50 m and negative anomalies of −50 and −30 m over the North Atlantic and the eastern Europe, respectively. In the AGCM simulation (Fig. 4), the spatial pattern of the positive anomaly of z500 during the summer season (JJA) is well simulated over Europe, but not the amplitude. The simulated maximum is just about 30–40 m. The negative anomaly over the eastern Europe is also simulated, even though it appears further east. To the north of 60°N, the simulated z500 anomaly is negative, whereas the observed anomalies are positive.

The precipitation field from Xie–Arkin data (Fig. 3a of FS10a) during JJA 2003 shows a deficit of precipitation over the entire Europe up to 35°E. The daily mean precipitation anomaly is below 1–1.5 mm/day, with a maximum negative value centered between northern Italy and southern Germany. The precipitation in the simulation also exhibits a negative anomaly (Fig. 5a), but it is more intense over eastern France and Poland. A major deficiency of the simulated precipitation is positive anomalies over the Mediterranean basin and over the North Sea, probably due to incorrect parametrization of convection induced by the very warm SST. In the western Sahel, the model does not generate as much rainfall as it is in Xie–Arkin data, and the observed precipitation pattern in the tropical Indian Ocean is shifted northward towards the Arabian Sea.

During JJA 2003, the soil is very dry (Fig. 3b of FS10a) with a negative anomaly of 10–15% of saturation, due to the below-normal precipitation during the previous spring season (not shown). Results of soil moisture anomaly from the simulations (not shown) have values less than 7.5%. This is the effect of an unrealistic rainy spring season by the COLA model (not shown). Therefore, the possible effect of the reduced soil wetness in enhancing the heat wave during JJA is missing in the simulation. It is quite likely that an appropriate treatment of the soil wetness in the simulation would improve the results, since previous studies (Ferranti and Viterbo 2006; Fischer et al. 2007)

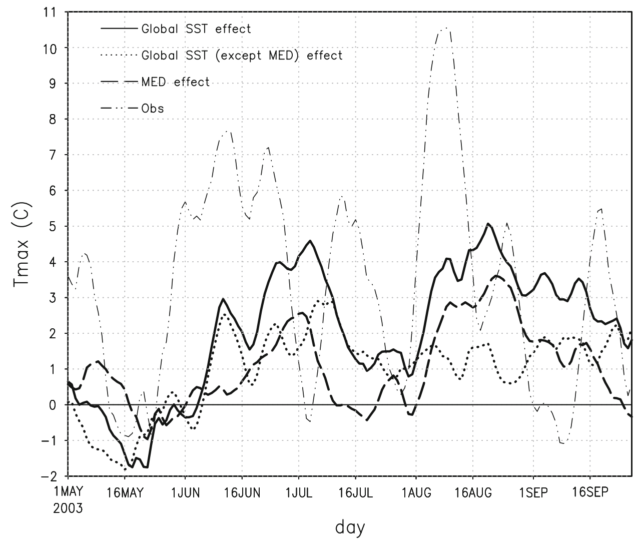


Fig. 3 Time-series of the ensemble mean T'_{max} (°C) from global SST experiment (*solid*), from the SST outside the Mediterranean area experiments (*dotted*), from the Mediterranean SST (*dashed*) and observed (*dotted-dashed*) averaged over (1°W–10°E, 43°N–50°N). The results are filtered with a 7-day average. (°C)

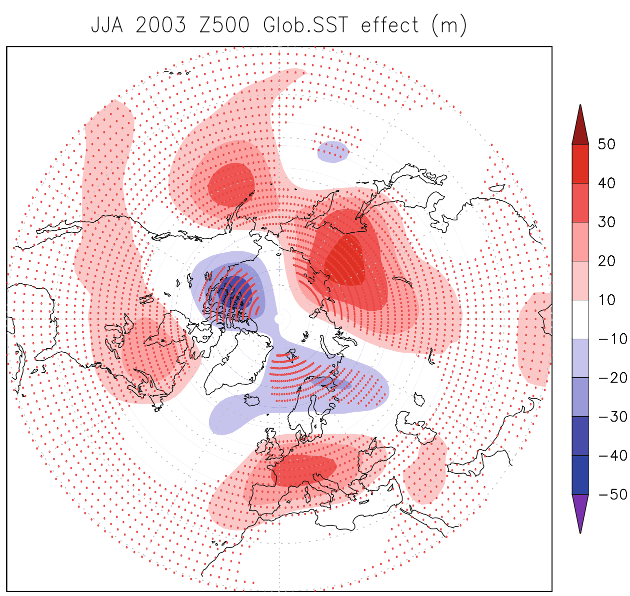


Fig. 4 JJA 2003 z500 anomaly (m) from the COLA AGCM global SST experiment, showing the global SST effect in the European heat wave.*Red dots* indicate regions where results are significant at more than 90% significant level

suggest the importance of the soil moisture–atmosphere interaction in enhancing the heat wave.

The results from the control simulation with the COLA AGCM show that the main characteristics of the heat wave are reproduced given the global observed SST as external forcing. However, the ensemble mean amplitude of the heat wave is underestimated. The low amplitude may be related to the "passive" response of the atmosphere to the SST warming and the absence of land effects. Comparing the observed response with the control run ensemble members during JJA and especially August (affected by the strongest warming), the observed values are well within the ensemble spread of the model forced response (Fig. 6). This is further supported by Fig. 7a which shows that the observed mean T'_{max} during August is well within the spread of model-forced response for averages over (1°W–14°E, 43°N–50°N). The same is true for the maximum temperature in August (Fig. 7b). These results confirm the influence of SST in forcing the heat wave of 2003. Since extra-tropical SST anomalies are largely forced by the atmosphere, the 2003 heat wave appears to be a good example of the atmosphere–ocean and atmosphere–land interactions reenforcing each other to produce a major heat wave.

The study by Vautard et al. (2007) shows that hot summers in the European area are preceded by winter rainfall deficits over southern Europe. Their result emphasizes the critical role of the soil water reservoir of the Mediterranean regions in affecting the European summer climate. The lack of soil moisture results in reduced evapotranspiration and latent cooling leading to an increase in surface temperature (Ferranti and Viterbo 2006). The study by Fischer et al. (2007) suggests that soil moisture perturbations can affect continental-scale circulation and that there is a positive feedback between the two resulting in an amplification of the summer European temperature anomalies. In fact, results from Seneviratne et al. (2006) confirm that, in this region, there is an increase in temperature variability mainly due to feedbacks between the land surface and the atmosphere. The present work does not investigate the possible role of initial soil moisture anomalies. However, it is quite reasonable to think that dry soil induced by reduced rainfall in the previous season may contribute to enhance the heat wave. Analyzing the two warmer ensemble members (solid and dashed lines in Fig. 8a) with the two colder (dotted and dash-dotted lines) during the month of August and comparing the respective soil moisture anomalies (Fig. 8b) in the area under question, the driest ensemble is also the hottest and the wettest is the coolest, as expected. Beside this feedback over land, a major model deficiency is the occurrence of convection over warm Mediterranean where in observations there is a large scale descending motion.

In analogy to the EOF analysis on observed data in FS10a, an EOF analysis is performed also for the AGCM outputs of maximum temperature and z500 anomalies to show the dominant pattern and weather regimes. The first EOF of simulated T'_{max} (Fig. 9a) shows a very similar spatial pattern indicating the extended central European area to be the most affected as it was found for observed

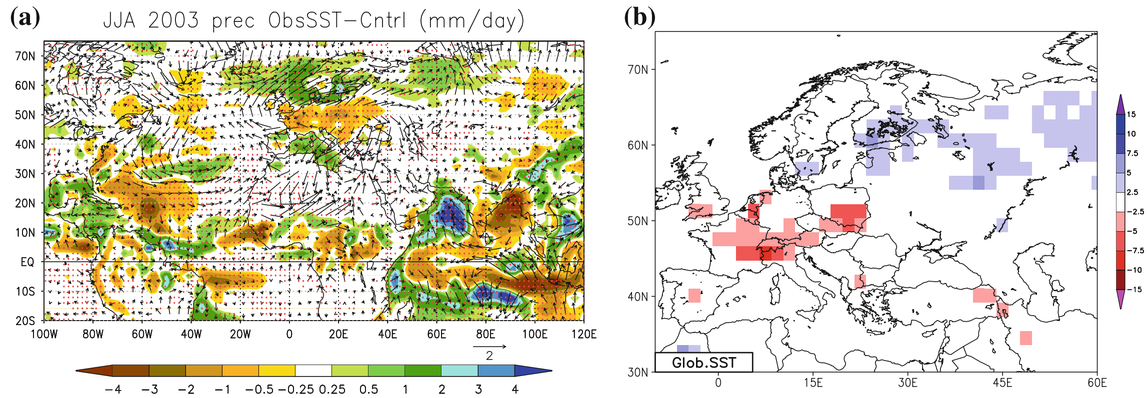


Fig. 5 **a** Precipitation anomaly during JJA 2003 in color (mm/day) and vectors of wind anomaly (m/s) at 1,000 hPa height level of COLA GCM simulation (*red dots* indicate regions where results are significant at more than 90% significant level). **b** JJA 2003 soil moisture anomaly (% of saturation) from the COLA AGCM simulation with the 2003 global observed SST as forcing

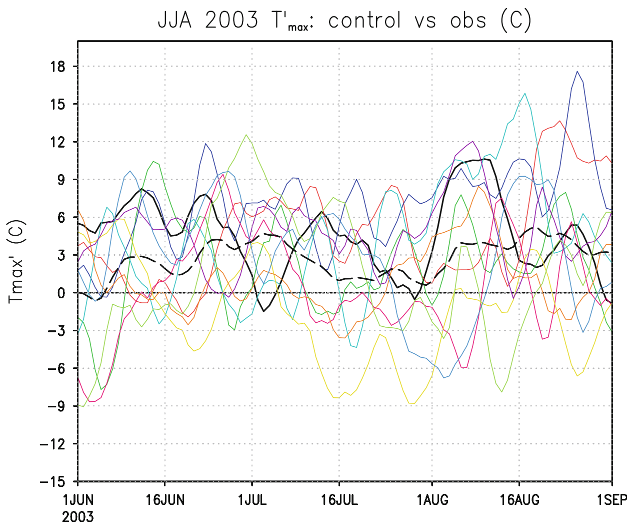


Fig. 6 Time-series of T'_{max} (°C) from 01 Jun to 01 Sep 2003 in the area (1°W–14°E, 43°N–50°N): in color each of the 10 ensemble members of the control simultation ("OBS.SST minus CLIM.SST"); in *black solid line* the observations and in *dashed black line* the mean of the ensemble members

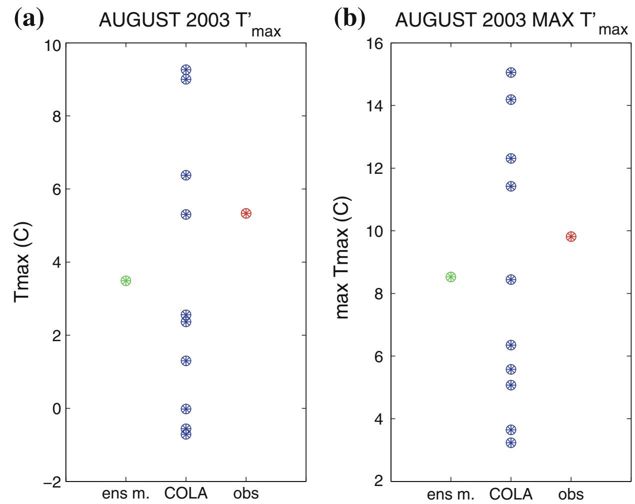


Fig. 7 **a** Mean August 2003 T'_{max} (°C) and **b** max August 2003 T'_{max} for the control simulation in the area (1°W–14°E, 43°N–50°N): in *blue* model ensemble members, in *green* model ensemble means and in *red* observations

T'_{max}. This pattern is dominant during both June and August (Fig. 9b), the time when the two main events occurred. The second EOF shows just the south-western European area affected by very warm temperatures (Spain, France and north-central Italy included), but was dominant just during mid-June up to mid-July (Fig. 9c, d). The results with observed T'_{max} showed instead the north-western part as the most affected, so including also Great Britain. The EOFs are calculated also for z500 anomalies to identify the weather regimes when forcing the model with observed SSTs. The calculation is done for the ensemble mean. The results show distinctly the two patterns: the Atlantic Low (the leading mode), lasting for almost the entire summer, but most dominant during June and half of July (Fig. 10a, b) and the blocking condition during the first part of June and exceptionally dominant during August (Fig. 10c, d). These results resemble the patterns found with observed data, with the only exception that the Atlantic Low regime (13.1% variability), most dominant in the simulation, was overtaken by the blocking condition with just 14.6% of total variability.

4 Influence of SST excluding the Mediterranean Sea

A previous study (Feudale and Shukla 2007) analyzed the influence of the Mediterranean SST alone, and showed that the structure of the heat wave could be simulated with the Mediterranean SST as the only forcing. The present study has shown that the SST anomalies over the northern part of North Atlantic, the North Sea and Baltic

Sea, had strong influence in producing the heat wave. To test this hypothesis of possible influence or effects of the SST of all oceans but not including the Mediterranean Sea, two other experiments were performed: one imposing just the observed Mediterranean SST in the nine month simulations and leaving climatological SST elsewhere ("OBS.MED") and the other imposing the observed SST elsewhere and leaving the Mediterranean Sea with climatological SST ("CLIM.MED"). Table 1 summarizes the specifications for these simulations, both with ten ensemble members. The effect of SST exclulding the Mediterraenan Sea could be determined in the differences "CLIM.MED minus CLIM.SST" and "OBS.SST minus OBS.MED". An average of the two results is used to explain the influence of global SST except the Mediterranean Sea.

Figure 3 displays the time series of T'_{max} of the heat wave simulation and the sensitivity experiment testing the influence of the global SST except the Mediterranean Sea in the area where the heat wave had the biggest impact (1°W–10°E, 43°N–50°N). The effect of the oceans outside Mediterranean is comparable to the global SST contribution in the first half of the summer. From August onward, the temperature anomalies are still positive, but less than the global SST simulation and Mediterranean SST effect. However, the spatial distribution of T'_{max} (Fig. 11a) shows seasonal (JJA) warm anomalies in the whole European region, more enhanced in Spain and France. In the continental Europe and the Mediterranean area the results of rainfall simulation (Fig. 11b) show a dry season, and lower than normal precipitation are also found in the Sahel, opposite to what was found in the experiment of the warm Mediterranean SST alone analyzed in Feudale and Shukla (2007), supporting the hypothesis of the Mediterranean-Sahel link by Rowell (2003).

In the simulation, the soil moisture in Europe (Fig. 11d) is also close to normal, not showing any trend toward either a drier or wetter soil. The z500′ (Fig. 11c) has a dipole pattern in the European area, positive over Europe and negative around 60°N, with a maximum positive anomaly over eastern Russia.

These results suggest that the influence of SST anomalies outside the Mediterranean area are important in initiating the heat wave which could be further amplified by Mediterranean SST anomalies and soil wetness anomalies over the surrounding land areas.

5 Summary and conclusions

In this study the authors have investigated the influence of SST on the 2003 summer heat wave in Europe with some atmospheric GCM experiments. The difference between simulations with the COLA AGCM, where global observed SST and climatological SST were imposed, was analyzed. The model study, involving the simulation and idealized sensitivity experiments of the events with integrations from 1 January to 30 September of 2003, showed that the global SST anomaly was able to capture the major features of the 2003 summer European heat wave, except that the magnitude was half of what was observed. The lower magnitude of the simulated heat wave was partly because of a warm model climatology. The anomalies of the simulated geopotential field and soil moisture were also weaker compared to observations. Even though the ensemble mean model response was less

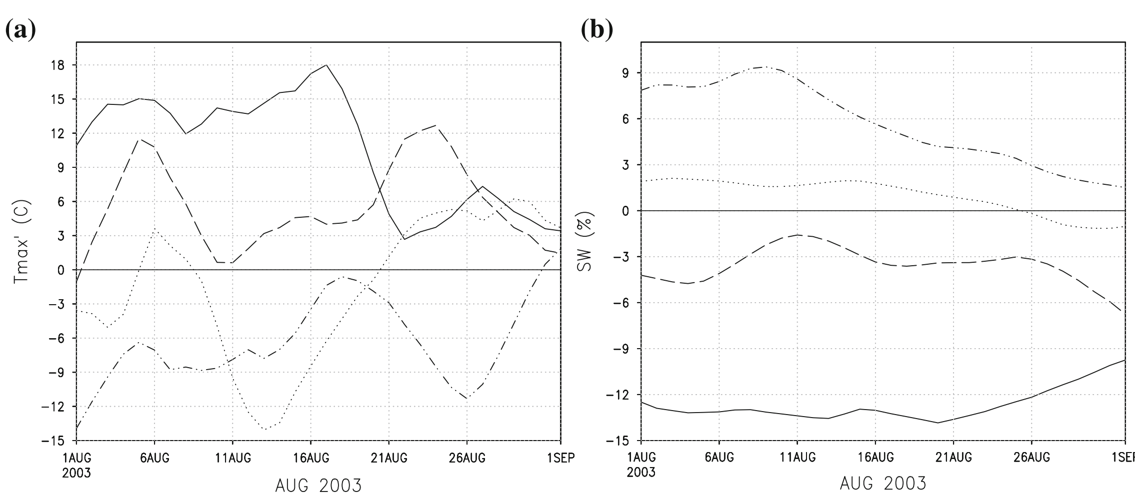
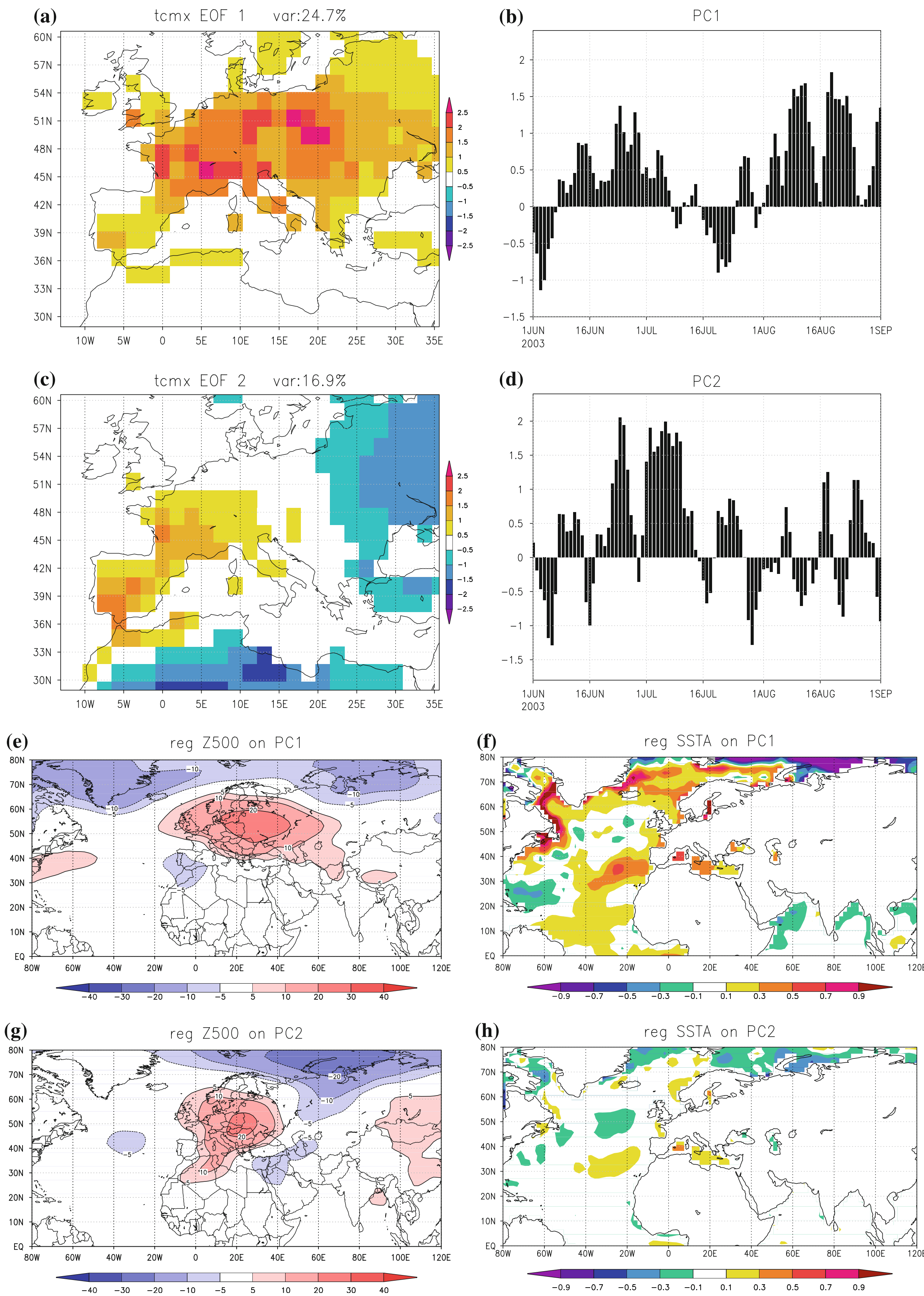


Fig. 8 **a** Time-series of the two warmest and coldest T'_{max} (°C) during August 2003 in the area (1°W–14°E, 43°N–50°N) and **b** the time-series of the respective soil wetness (%) represented with the same line style as in **a**


(a)
tcmx EOF 1 var:24.7%
(b)
PC1
1JUN
2003
16JUN
1JUL
16JUL
1AUG
16AUG
1SEP
(c)
tcmx EOF 2 var:16.9%
(d)
PC2
(e)
reg Z500 on PC1
(f)
reg SSTA on PC1
(g)
reg Z500 on PC2
(h)
reg SSTA on PC2

◀ **Fig. 9** EOF components of the COLA AGCM global SST experiment calculated between 1 Apr 2003 and 30 Sep 2003 in the area (12°E–35°W, 30°N–60°N): leading **a** EOF and **b** PC; second **c** EOF and **d** PC. Regression analysis of **e** $z500'_{max}$ and **f** SSTA on the first PC; **g** and **h** the same as **e** and **f** only for the second PC

than the observed values of temperature anomaly, the observation was well within the ensemble spread of the model. The results suggest that the global SST might have forced a circulation pattern conducive to a blocking situation in the European region, and the blocking situation in turn warmed up the land surfaces and the surrounding seas, including the Mediterranean Sea, North Sea and surrounding North Atlantic Ocean.

In FS10a a composite analysis of major past European heat waves showed the SSTA in the Mediterranean basin to be at least 0.5–1°C above the climatological mean, and warm North Sea and the surrounding parts of the North Atlantic as common features for European summer heat waves. In Feudale and Shukla (2007), the effects of Mediterranean SST alone was analyzed. It was shown that while Mediterranean SST anomalies are not responsible to produce the heat wave: once a heat wave is initiated, warm Mediterranean SST anomalies reinforce the heat wave. In the present paper, additional experiments were used to study the effect of the SST outside the Mediterranean area. It has been found that the SST anomalies in the North Sea and surrounding North Atlantic reduce the baroclinicity in the European region (mechanism suggested and speculated in FS10a), prevent baroclinic waves to influence the Mediterranean area, and enhance blocking and following dry conditions, giving rise to heat waves. Therefore the SST anomalies made the intense heat wave more likely but far from certain, as internal atmospheric

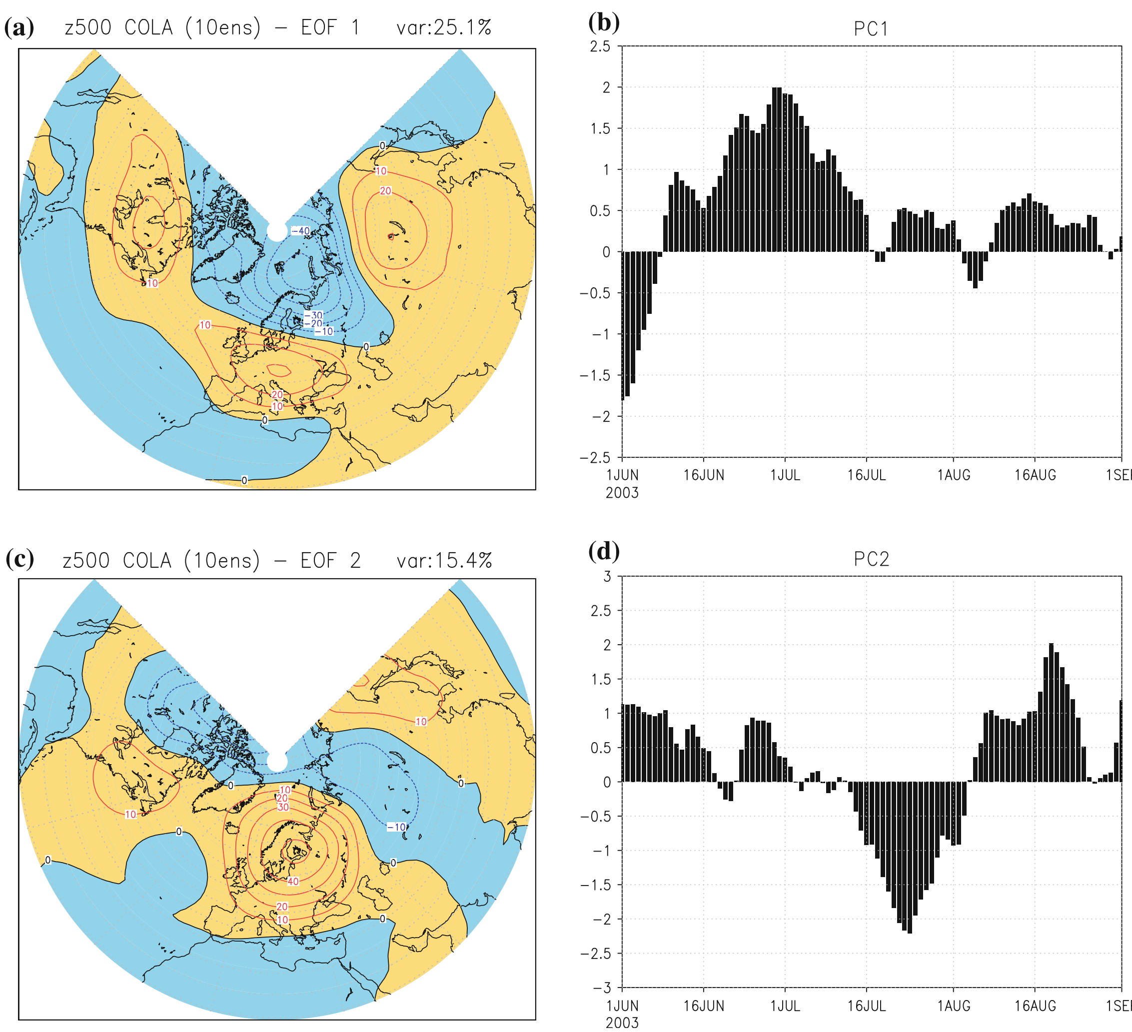


Fig. 10 EOFs of COLA AGCM global SST experiment z500 anomaly, calculated between 1 Apr 2003 and 30 Sep 2003 in the area (120°W–150°E, 20°N–85°N): **a** and **b** first EOF and PC; **c** and **d** second EOF and PC

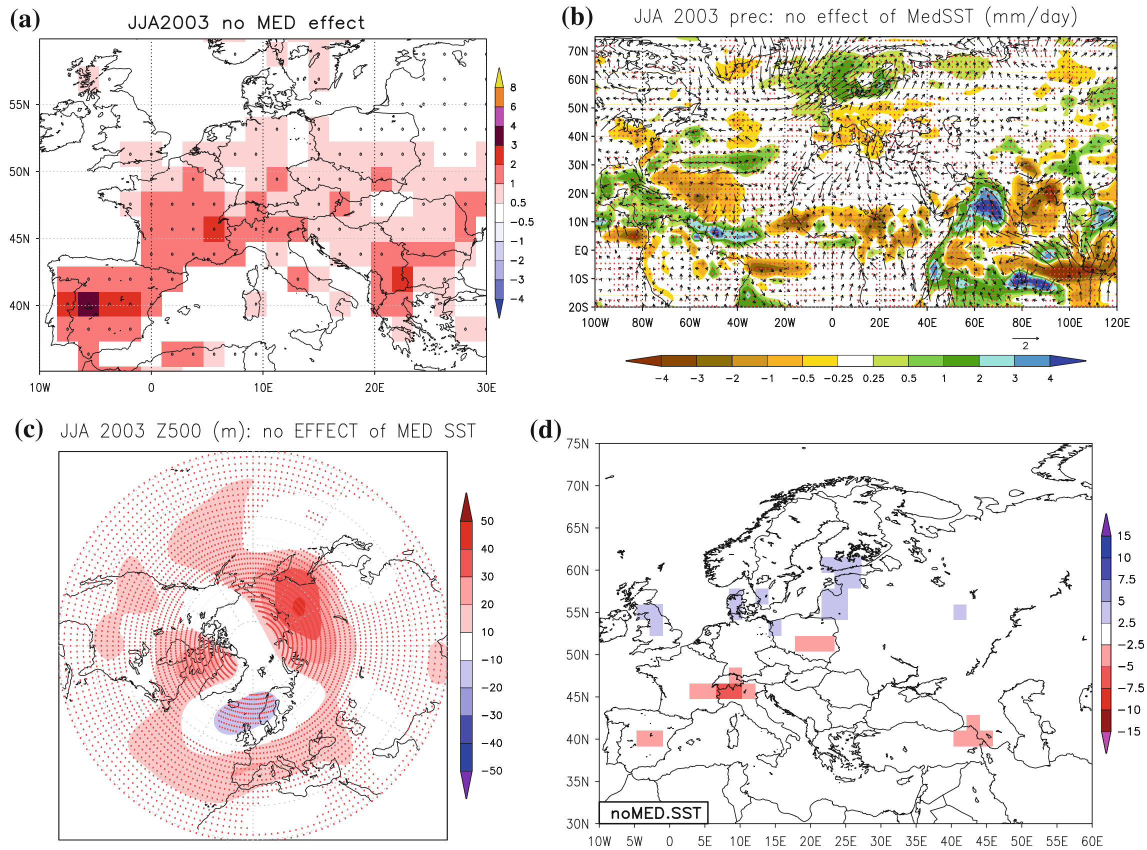


Fig. 11 Influence of the SST outside the Mediterranean region during JJA 2003 from COLA AGCM sensitivity experiment: **a** T_{max} (°C), **b** precipitation anomaly (mm/day) and vectors of wind anomaly at 1,000 hPa height level; **c** z500 anomaly (m); **d** soil moisture anomaly (% of saturation). *Dots* in **a**, **b** and **c** indicate regions where results are significant at more than 90% significant level

variability could have led to other outcomes as shown in Figs. 6 and 7.

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