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Response to the summer 2003 Mediterranean SST anomalies over Europe and Africa

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Abstract

The sensitivity of the atmospheric circulation to the warm Mediterranean sea surface temperature (SST) anomalies observed during summer 2003 (July and August) is studied using the European Centre for Medium Range Weather (ECMWF) forecast model. A control integration imposes climatological Mediterranean SSTs as a lower boundary condition. The first sensitivity experiment uniformly increases these Mediterranean SSTs by 2K; the approximate mean observed in the 2003 summer season. A second experiment then investigates the additional impact of the SST distribution by imposing the observed SST summer anomaly.

The response of the atmospheric circulation in the European area shows some resemblance to the observed anomaly. The weakness of this response suggests, however, that the warm Mediterranean played a minor role, if any, in maintaining the anomalous atmospheric circulation as observed in summer 2003. Increasing SST in the Mediterranean locally leads to an increase in precipitation, particularly in the western Mediterranean. Furthermore, significantly increased Sahelian rainfall is simulated, deriving from enhanced evaporation in the Mediterranean Sea. In the ECMWF model the anomalously high moisture is advected by the climatological Harmattan and Etesian winds, where enhanced moisture flux convergence leads to more precipitation. The associated diabatic heating leads to a reduction of the African easterly jet strength. A similar Sahelian response has been previously documented using a different atmospheric model, increasing confidence in the robustness of the result. Finally, the results are discussed in the context of the seasonal predictability of European and African climate.

1 Introduction

The climate of the summer season of 2003 was anomalous over the west European and north Africa continents in three respects. Firstly, the summer of 2003 was marked by anomalously high, and in some regions record, temperatures over Western Europe. Levinson and Waple (2004) report that even annual mean temperatures across Mediterranean and northwestern Europe were in the 98th percentile of the 1961-1990 distribution in 2003, but that in the summer months in particular, warm anomalies exceeded 5^oK across much of this region. In many regions the summer maxima, or the nighttime minima, were unprecedented in the modern instrumental record (e.g., Grazzini et al., 2003). In addition to accelerated glacier retreat over the Alps, associated socio-economic impacts included increased heat-related mortality (e.g. Stott et al., 2004; Vandentorren et al., 2004) and disruption of nuclear power generation.

The second aspect of the anomalous season pertains to the warm sea surface temperatures that were observed over this region. The mean SST anomaly during July–August 2003 amounted to about 2.1K, with a marked horizonal gradient. This is seen in Fig. 1, which shows the mean SST anomaly for the period July and August 2003 (see also Grazzini and Viterbo, 2003) relative to the 1958-2002 ERA-40 climatology. The peak in SST anomalies is far smaller in the south-eastern end of the ocean basin. In the western part of the Mediterranean, SST anomalies exceeded the long-term standard deviation, obtained from ERA-40 reanalysis data (1958–2002), by more than a factor of three (not shown)!

The third anomalous feature of the 2003 summer climate relates to the rainfall of the West African Sahel region. The Sahel region has been undergoing a long-term period of drought since the late 1960s (Nicholson et al., 1998; Nicholson, 2000; Rowell, 2003; Dai et al., 2004). In this context, Levinson and Waple (2004) report that the summer rainy seasons of 2003 was the second wettest since 1990, with the June–September rainfall total exceeding the average (1979–95) by more than 100mm.

Considering these three phenomena of high European temperatures, warm Mediterranean SSTs and anomalous rainfall in the Sahel, it is natural to ask if there is a causal link between them. For example, did the warm SSTs contribute to, or result from, the warm summer European air temperatures (or both if a positive feedback exists)? On the other hand, it is possible that both are independent manifestations of a third forcing factor; the anomalous large-scale circulation circulation. The fact that Mediterranean SSTs could have a significant role in the local and non-local climate has led to them becoming the focus of a new CLIVAR subproject: MedCLIVAR (Mediterranean Climate and Variability and Predictability) project[1], which amongst others aims to provide an assessment of the possible feedbacks of the Mediterranean dynamics in the global climate system, including the effect of Mediterranean SSTs on the export of moisture to regions around it, on Sahel precipitation, on large scale atmospheric circulation.

Applying canonical correlation analysis to observational data Xoplaki et al. (2003) found a strong link between the anomalous atmospheric circulation and Mediterranean SST anomalies during the summertime. The leading canonical mode closely resembles the anomalies observed in summer 2003. While statistical analysis techniques as used by Xoplaki et al. (2003) are useful for identifying possible links between phenomena, they struggle with the above issues of causality or feedback. Thus, observational studies can be usefully supplemented by modelling studies, in which fully controlled experiments can be conducted. From the plethora of possible interactions, this paper aims to use a controlled modelling study to address the specific question of whether the observed Mediterranean SSTs anomalies could have contributed to either the anomalous Sahelian rainfall or the warm European air temperatures.

Numerous studies (e.g. Palmer, 1986; Rowell et al., 1992; Janicot et al., 1996; Vizy and Cook, 2001; Wang et al., 2004) have highlighted the central role of both local and non-local SSTs in determining regional precipitation anomalies in the Sahelian region. Rowell (2003) went on to specifically focus on the relationship between Mediterranean SSTs and Sahelian rainfall and supplemented a statistical analysis of the former relationship with just such an idealized climate modelling study, which indicated a significant influence of Mediterranean SSTs on Sahel rainfall. The suggested mechanism by which this occurs is the enhancement of lower tropospheric moisture by enhanced latent heat fluxes over the Mediterranean basin. This is advected south by the mean flow increasing the low-level moisture convergence over the Sahel, ultimately increasing rainfall there.

The first aim here is to confirm the Mediterranean-Sahel link ofRowell (2003) using a different atmospheric model, and to provide an analysis of the mechanisms involved. The second aim is to examine whether there is a similar causal influence of Mediterranean SST anomalies on European circulation and air temperatures. Some potential causes for the origin of the blocking high pressure and associated warm SSTs are suggested by Black et al. (2004) and Cassou et al. (2005), while this article discusses the predictability of such events.

The paper is organized as follows. In the following section the experimental setup is described. This is followed by a section describing the results. The focus is on the dynamical and thermodynamical response to an anomalously warm Mediterranean Sea. Finally, the results are discussed and the conclusions are given.

2 Methodology

To carry out the investigation, the atmospheric model component of the European Centre for Medium Range Weather Forecast (ECMWF) Integrated Forecast System (IFS) is used. Specifically, the numerical experimentation is based on model version (cycle) 28R1, which was used operationally at ECMWF from 9 March to 28 June 2004. The horizontal resolution used for these experiments is T_L159 (approx. $1.125^o \times 1.125^o$) with 40 levels in the vertical. The performance of earlier model cycles in simulating the observed climate is described elsewhere (e.g., Brankovic and Molteni, 2004; Jung, 2005; Jung et al., 2005). In the context of the present study it is worth mentioning that the implementation of a more realistic aerosol climatology, particularly in northern Africa and the Middle East, in 2003 has led to significant improvements of the model climate in the region

[1] http://clima.casaccia.enea.it/medclivar

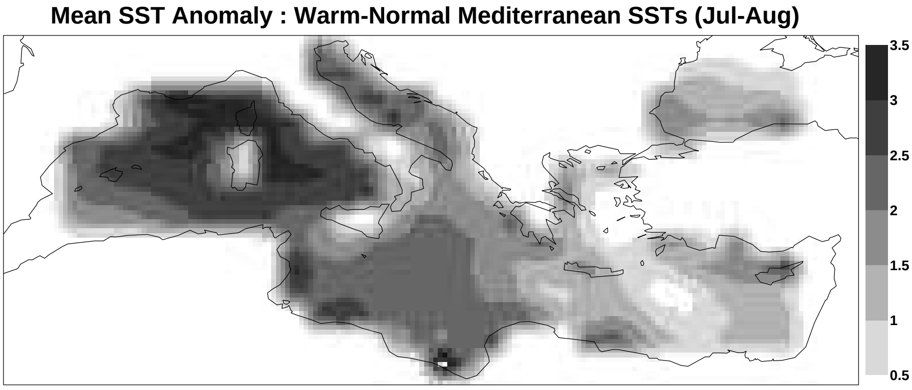

Figure 1: Observed SST anomalies (K) for July and August 2003 from the operational ECMWF analysis, relative to the 1958–2002 ERA-40 climatology.

considered in this study (Tompkins et al., 2005; Rodwell and Jung, 2005).

In total, three experiments were conducted. A control integration (termed CNTL, hereafter) simply imposes climatological SST fields globally as lower boundary conditions. The first sensitivity experiment examines the impact of the *mean* Mediterranean SST anomaly by increasing the climatological Mediterranean SSTs everywhere by 2K, the approximate average perturbation observed during the 2003 summer season. This experiment is referred to as MEDAV.

A further sensitivity experiment is added since examination of the observed SST anomalies reveals significant horizontal gradients (Fig. 1). In particular, the anomalies in summer 2003 are rather small in the eastern Mediterranean Sea; a region which has been identified by Rowell (2003) using observational data as having potentially the largest impact on Sahel rainfall. In the second sensitivity experiment the observed Mediterranean SST anomalies (as depicted in Fig. 1) have therefore been added to climatological SST fields (experiment termed MEDOB). The difference between the two sensitivity experiments documents the impact of SST gradients. A summary of the three experiments is given in Tab. 1.

For each of the above experiments 3-month long integrations were started from ERA-40 reanalysis data (Uppala et al., 2005) for 1 June 1958–2002, a total of 45 integrations for each experiment. All results presented in this study are based on the months of July and August only (the first month is discarded), in order to ensure independence of the different experiments from the initial conditions.

Table 1: Summary of the experiments used in this study.

Abbreviation	Model Cycle	Resolution	Period	SST
CNTL	28R1[1]	T_L159L40	1958–2002	Climatological SST
MEDAV	28R1[1]	T_L159L40	1958–2002	Climatological SST& 2K SSTA throughout the whole Mediterranean
MEDOB	28R1[1]	T_L159L40	1958–2002	Climatological SST & Summer 2003 SSTA in the Mediterranean

[1] Operationally used at ECMWF from 9 March 2004 to 28 June 2004.

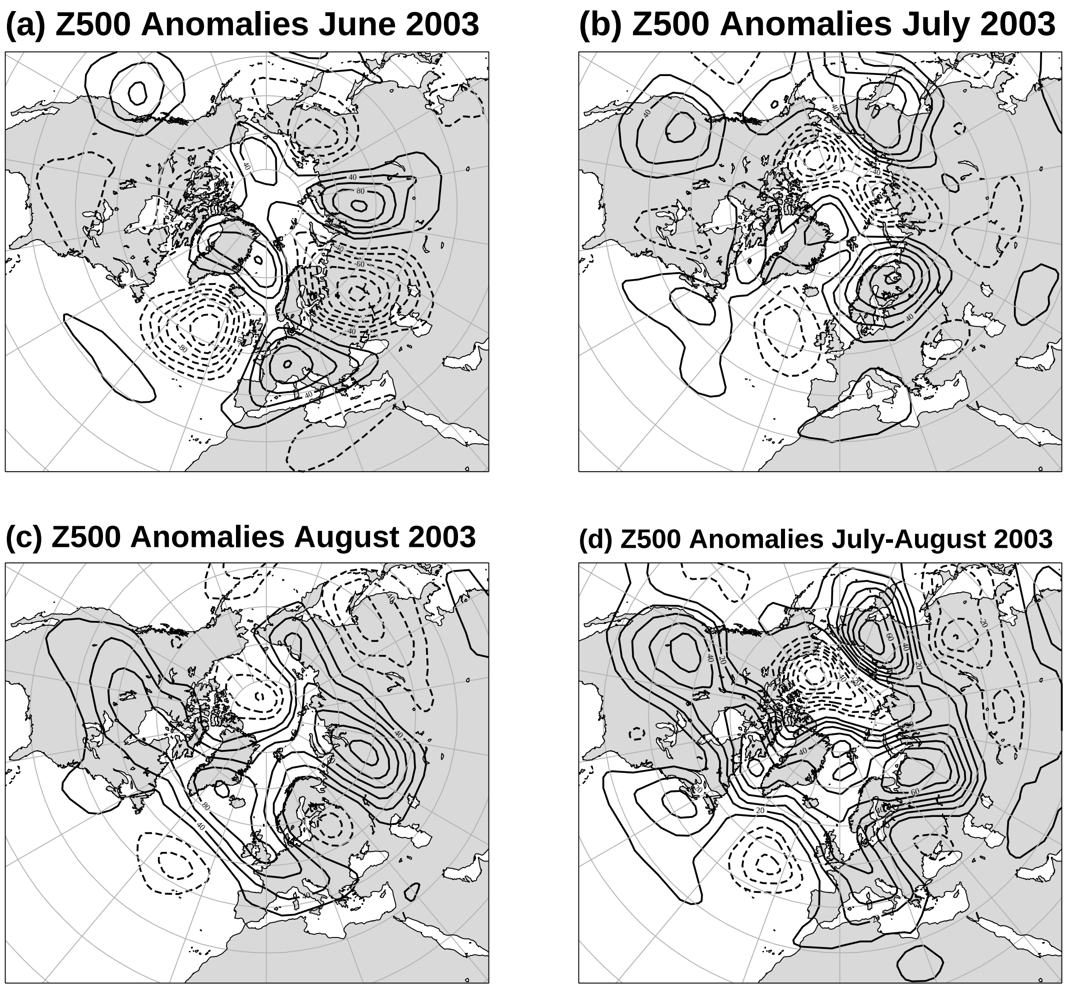

Figure 2: Observed Z500 anomalies (m) for (a) June, (b) July, (c) August, and (d) July–August 2003. The contour interval is (a)–(c) 20m and (d) 10m, with negative values shown with dashed contours, and the zero line has been omitted. Anomalies were computed with respect to the ERA-40 climatology (1958–2002).

3 Results

3.1 Dynamical Response

Over Europe, a persistent high pressure block characterized much of the period under study, which is depicted in Fig. 2 in terms of 500 hPa geopotential height (Z500) fields (see also Black et al., 2004; Cassou et al., 2005). The anomalies are computed from the ECMWF operational analyses relative to the ERA-40 climatology (Uppala et al., 2005) and show that the months of June and August in particular exhibited a strong anomalous quadrupole structure, with the southern-most peak in the high pressure ridge anomaly occurring over France and Germany. In fact, the particularly strong negative Z500 anomaly that stands out during June 2003 over Eastern Europe and Russia was accompanied by one of the coldest Junes on record there (Levinson and Waple, 2004).

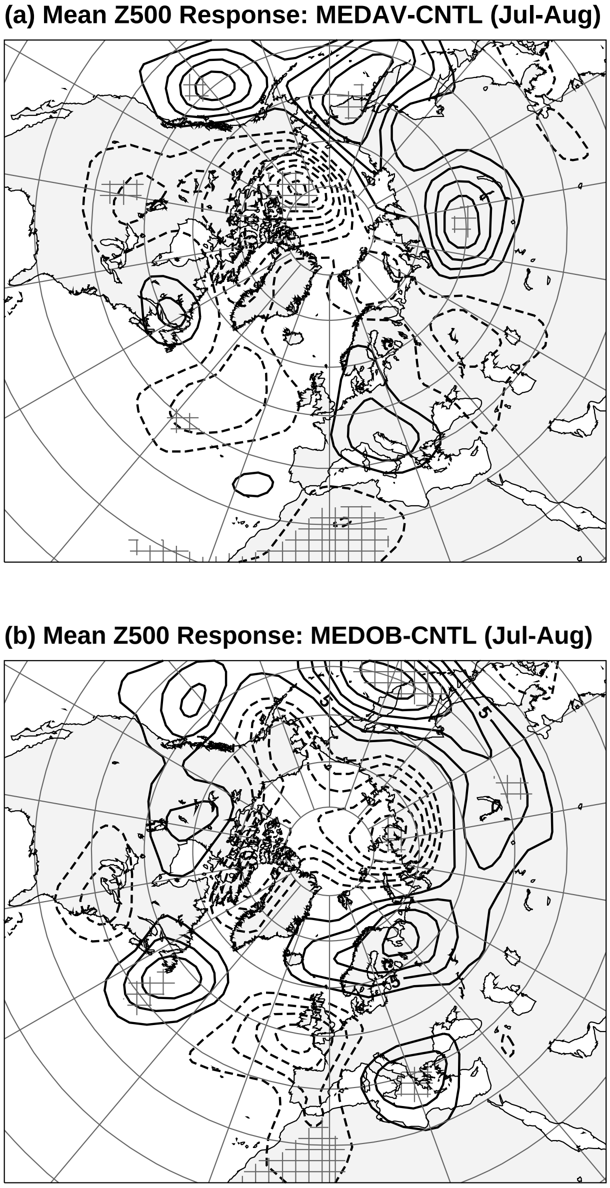

Figure 3: Difference of mean Z500 fields (contour interval is 2.5 m) for July-August: (a) MEDAV−CNTL and (b) MEDOB−CNTL. Results are based on 45 summers. Statistically significant differences (at the 95% confidence level) are hatched.

The atmospheric response to anomalously warm Mediterranean SSTs in the model is shown in terms of Z500 in Fig. 3 for both sensitivity experiments (note the different contour interval to Fig 2). In both cases the impact of the SST anomaly is to produce a mid-latitude wave-like feature extending from North America towards Europe, not unlike those observed in summer 2003 (Fig. 2). The cyclonic and anti-cyclonic circulation anomalies in the eastern North Atlantic and further downstream, respectively, are particularly interesting features for they lead to anomalous warm air advection in western Europe. The magnitude of the Z500 anomalies, however, is relatively small amounting to about 20–30% of those observed in summer 2003. It should be noted that in neither experiment are the Z500 anomalies statistically signifi cant at the 95% level, except for the positive Z500 anomaly in the central Mediterranean Sea in MEDOB. This does not necessarily mean, however, that the response is an artifact due to sampling variability (Nicholls, 2000); rather, the results suggest that if summertime Mediterranean SST anomalies have an impact on the atmospheric circulation over Europe, then this impact is

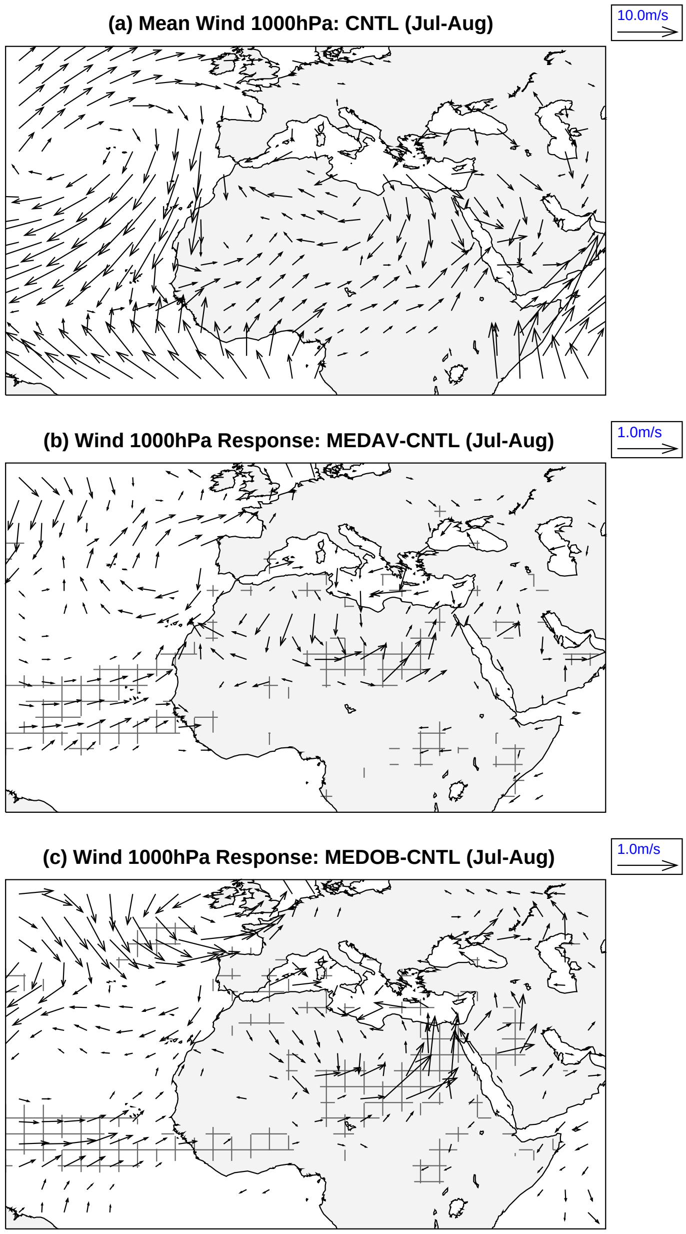

Figure 4: (a) Mean wind vectors at 1000 hPa from the control integration. Also shown are mean wind vector differences at 1000 hPa: (b) MEDAV−CNTL and (c) MEDOB−CNTL. Results are based on 45 summers. Areas where the difference of the magnitude of the wind vectors is statistically significant (at the 95% confidence level) are hatched in (b) and (c). Reference vectors (in m/s) are also given.

likely to be small compared to the level of natural variability.

Climatological near-surface (1000 hPa) winds from CNTL are shown in Fig. 4a. The main features are the north-easterly and south-easterly trade winds in the subtropical Atlantic, the southerly on-shore monsoon flow in the Gulf of Guinea, which provides moisture to the African intertropical convergence zone (ITCZ), which attains its northern-most position during this period of the year. The north-easterly flow known as the Harmattan wind, originating in the mid-Mediterranean and then moving over the Sahara, is apparent. The Harmattan rises over the low-level moist south-westerly monsoon flow to form the elevated dry Saharan air layer (SAL). The

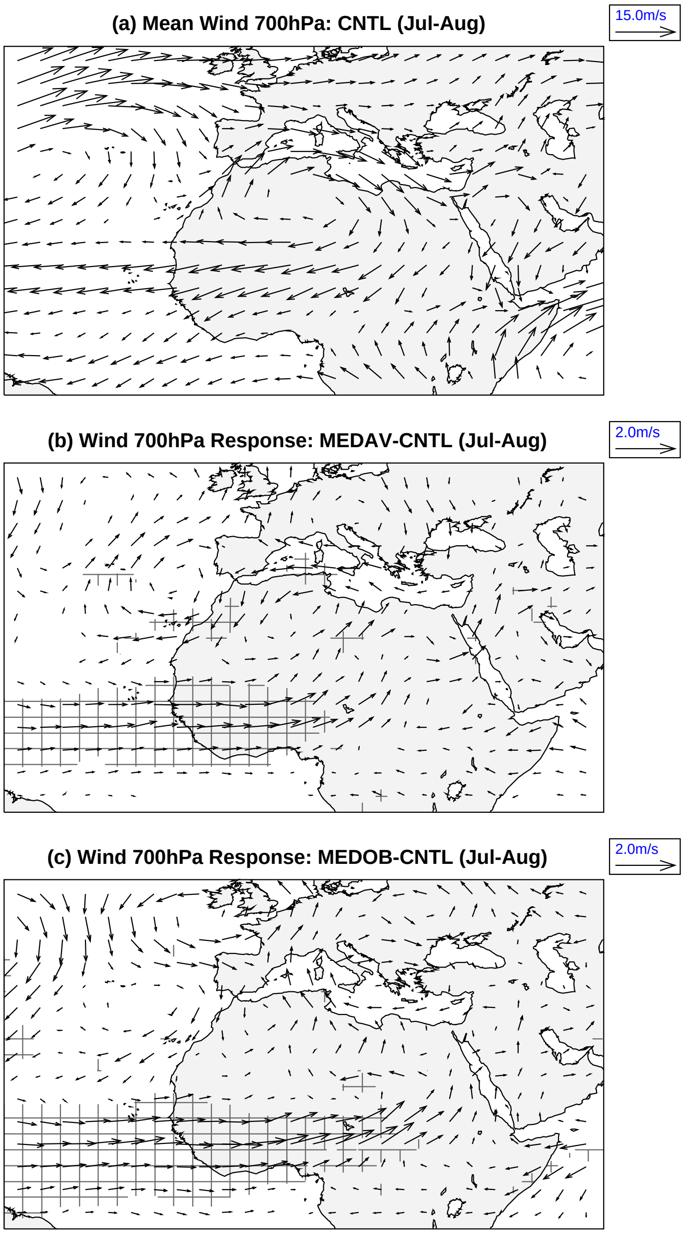

Figure 5: As in Fig. 4, except for the 700 hPa level.

strong near-surface north-westerly flow in the eastern Mediterranean region, the so-called Etesian wind, is also represented.

In both experiments, the broad wind response is similar. Over the Atlantic off the West coast of the Sahel there is a strong and significant deceleration of the low-level Easterlies flow (the statistical significance test is conducted for the wind magnitude only, changes in the vector direction are neglected). This zone is aligned with the western extension of the mid-tropospheric (700 hPa) African easterly jet (AEJ) and the ITCZ, identified by the low-level convergence zone in the upper panel. The confluence of the wind anomalies signifies enhanced convergence. This hints that deep convection may have undergone changes in response to the Mediterranean SST warm anomalies, which will be seen to be the case in the analysis of the precipitation fields below. Over north Africa the response is cyclonic, with the northerly flow over the Sahara strengthened, while the northerlies

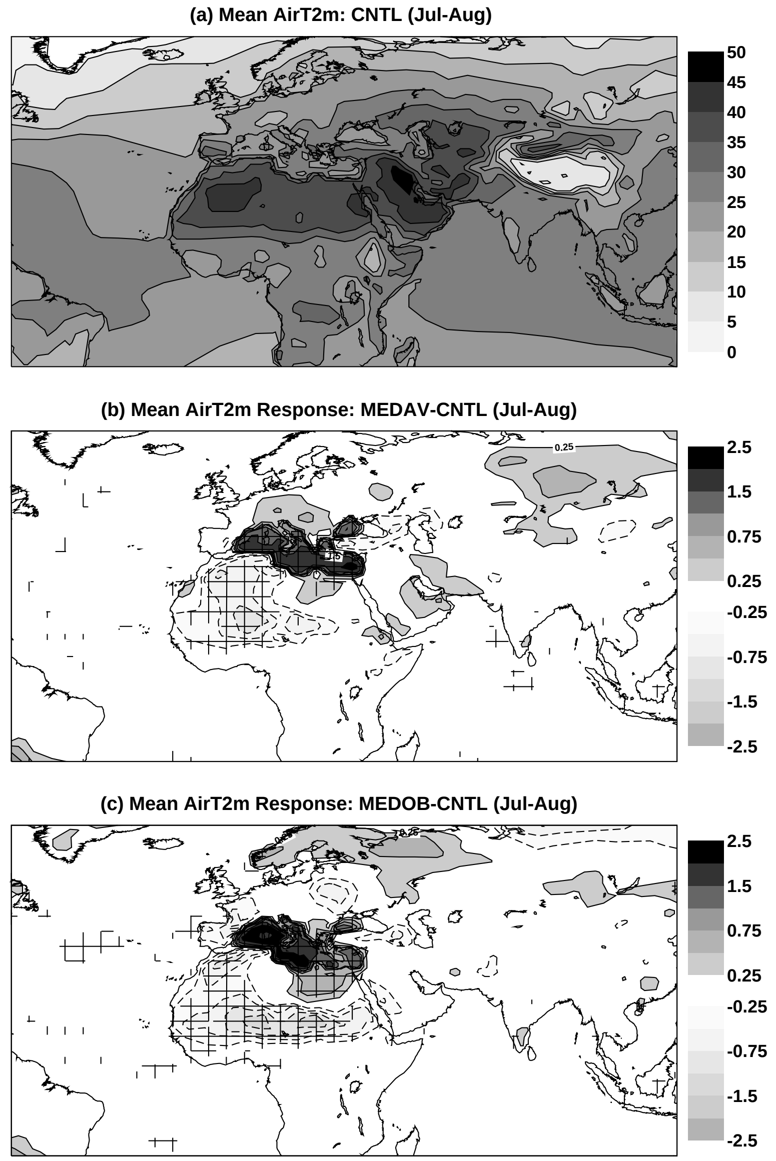

Figure 6: Same as in Fig. 4, except for 2m air temperature (°C).

over the northeastern Sahara significantly weaken. In addition to the Gulf monsoon flow, this flow is attributed with being a secondary source of moisture for the deep convection to the south. The fact that a similar dynamical response is found in both experiments is an indication of its robustness and that spatial SST gradients play a secondary role.

The low level wind response off the Atlantic coast of the Sahel indicate that deep convection and the associated AEJ were affected by the Mediterranean SSTs. Figure 5 shows this is indeed the case, and the 700 hPa winds that mark the rough height of the AEJ (Burpee, 1972) undergo a significant de-acceleration in both cases. Moreover, it is worth noting that the weakening of the 700 hPa easterly winds extends well into the tropical Atlantic.

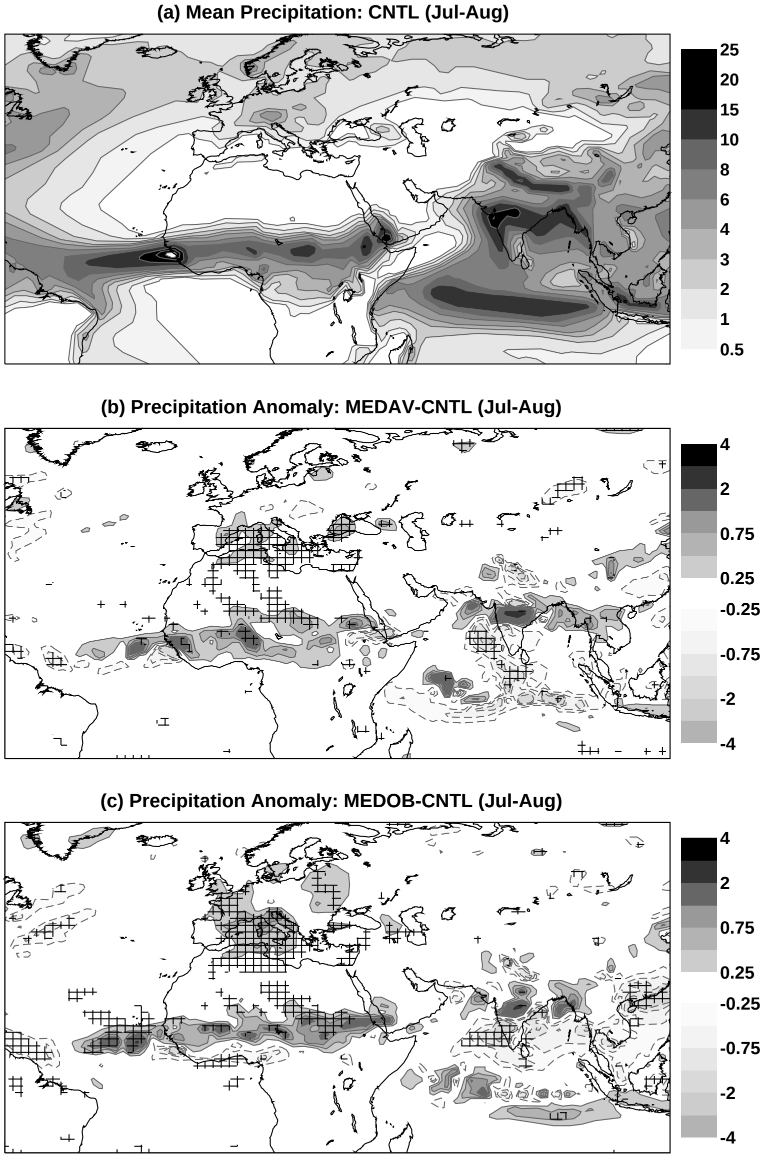

Figure 7: Same as in Fig. 4, except for total precipitation (mm/day).

3.2 Thermodynamical response

Most of the devastating effects of summer 2003 were related to large positive surface temperature anomalies over western and central Europe. It is therefore interesting to investigate the response of 2m air temperatures in the two experiments. The results are shown in Fig. 6. The near-surface temperature response over Europe is relatively small. This can be explained by the near-surface climatological circulation shown in Fig. 4a which is rather weak preventing warm air advection from happening. The anomalous warm boundary layer over the Mediterranean is a direct result of increased turbulent sensible heat fluxes over the ocean. Reduced near-surface temperature anomalies in the Sahel region, on the other hand, can be explained by reduced incoming surface short-wave radiation and increased near-surface evaporation due to increased rainfall.

The previous section indicated that a strong response in low level flow and the AEJ occurs to the mean or observed 2003 SST anomaly in the Mediterranean. The characteristics of deep convection and the monsoon

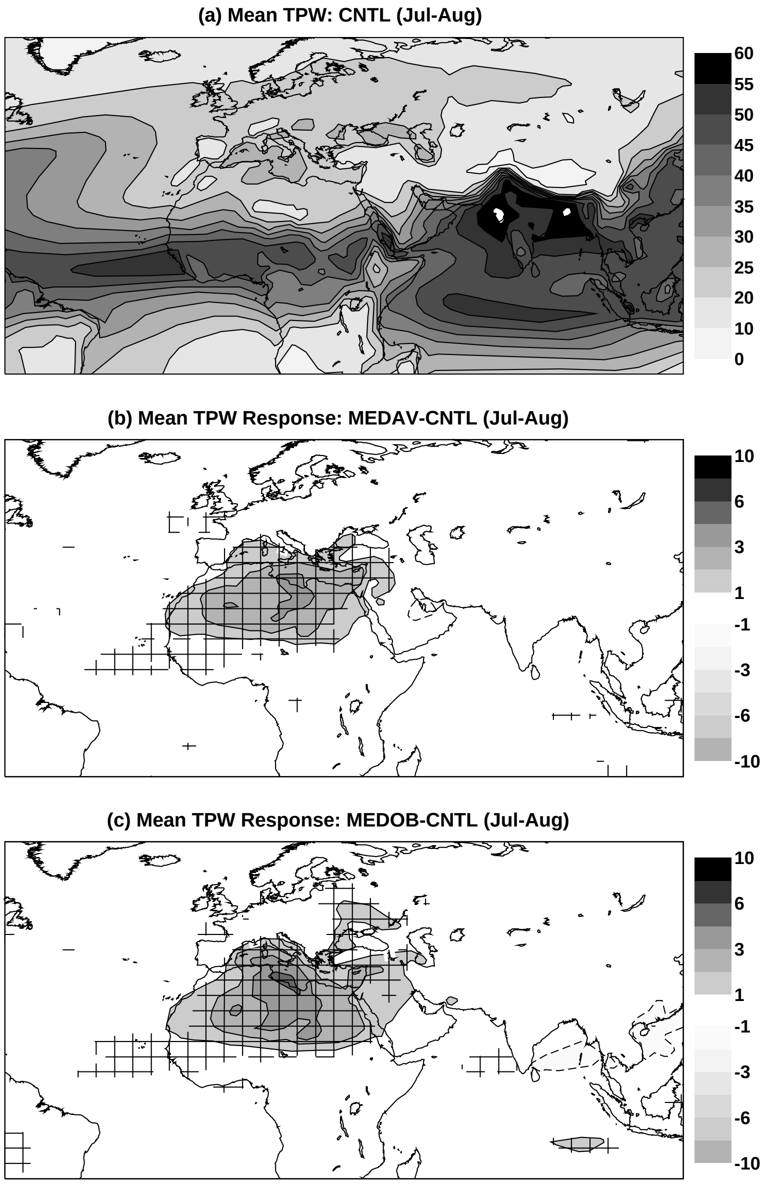

Figure 8: Same as in Fig. 4, except for total precipitable water (kg/m^2).

season rainfall are also likely to have altered in tandem. It is recalled that the Sahel experienced one of the wettest monsoon seasons of recent decades in 2003, and furthermore that Rowell (2003) also found an increased precipitation response to a warm Mediterranean anomaly. Figure 7 shows that this is also the case here, with increased rainfall throughout the Sahel in both experiments. Again, the fact that both experiments show a similar response in the Sahel region implies that the precipitation response to warm Mediterranean SSTs is a robust feature.

Both experiments also indicate an increase in precipitation directly over the Mediterranean itself. The total precipitation anomaly can largely be explained by increased convective precipitation rather than changes in rainfall produced by the large-scale cloud scheme responsible for the precipitation in fronts (not shown). Note that only a minor increase in convective activity is required to produce a statistically robust rainfall signal due to the extremely low rainfall in this region in summer. An analysis of Global Precipitation Climatology Project (GPCP) rainfall data (Huffman et al., 1997) indicated that this local model response was not validated by the observations, which suggests that the European dry conditions extended across the Mediterranean basin (not shown).

If the increase in Mediterranean SST influences other regions through its impact on the humidity budgets, then changes to the total column integrated water vapour (TCWV) fields should be apparent. Figure 8 indicates that the increase in TCWV is quite dramatic, with statistically significant increases of up to 3 kg m^{-2} spanning the entire north Africa region. There is little change to the TCWV anomalies if one applies the Mediterranean mean or observed SSTs. As one may expect, the increases in the TCWV are delimited to the south by the ITCZ. It is also apparent that the increases in SST do not impact the water vapour budget at all over the European continent. This is consistent with the lack of a near-surface response over Europe preventing moisture advection from occurring.

4 Discussion

4.1 Mechanism of the Mediterranean-Sahel link

The aim of this study was to investigate the impact of Mediterranean SST as observed in summer 2003 on the atmosphere. More specifically, two regions have been considered, that is, Europe and northern Africa.

A significant impact of Mediterranean SST anomalies on the African Sahel region to the south was found; most notably manifest as increased precipitation, in agreement with the anomalously wet summer season of 2003. This finding agrees with the modelling study of Rowell (2003), who showed that the primary effect of the warm Mediterranean SST was to enhance the local moisture that is advected by the mean flow over Sahel, enhancing deep convection there. It seems likely that this is also the case for the simulations conducted here, since increased atmospheric integrated water vapour was found over the Mediterranean and northern Africa. However, the dynamical response is such as to weaken the climatological near-surface northerly winds in northeastern north Africa (Fig. 4) potentially leading to reduced southward moisture transports. This tendency was counteracted, though, by increased near-surface winds further to the west.

In order to better understand the underlying mechanism, the column integrated moisture flux ($\mathbf{Q}(\lambda,\phi,t)$) is examined (see also Fontaine et al., 2003), which is given by the following expression:

$$\mathbf{Q}(\lambda,\phi,t) = \int_{p_0}^{p_s} q\mathbf{v}\frac{dp}{g}, \qquad (1)$$

where p is the pressure coordinate, p_s the surface pressure, p_0 the limit of integration (300 hPa in this study), q is the humidity and $\mathbf{v}$ the wind vector. The moisture flux $q\mathbf{v}$ can be divided into the mean component $\overline{q}\overline{\mathbf{v}}$ and the total anomalous flux, which itself can be subdivided into three components: $\overline{q}\mathbf{v}'$, $q'\overline{\mathbf{v}}$ and the correlation term $q'\mathbf{v}'$.

The total anomalous flux and its three subcomponents are shown in Fig. 9 for MEDOB. The total anomalous flux is dominated by the eastward component at 15^{o}N centred along the axis of the ITCZ and the African easterly jet (Fig. 9a). However, close examination also reveals a significant southerly anomalous humidity flux centred at 20^{o}E, bringing enhanced moist air from the Mediterranean into the deep convective zone. If the subcomponents of the moistures flux are separately examined, these two effects are clearly distinguishable. The westerly anomalous flux along the ITCZ is a result of the de-acceleration of the climatological easterly low-level and mid-level flow (Fig. 9c). This enhanced anomalous moisture flux from the Atlantic nicely supports one of the positive feedback mechanisms of Rowell (2003). On the other hand the enhanced southward advection of moisture from the Mediterranean Sea is dominated by the advection of the moisture anomaly by the mean flow

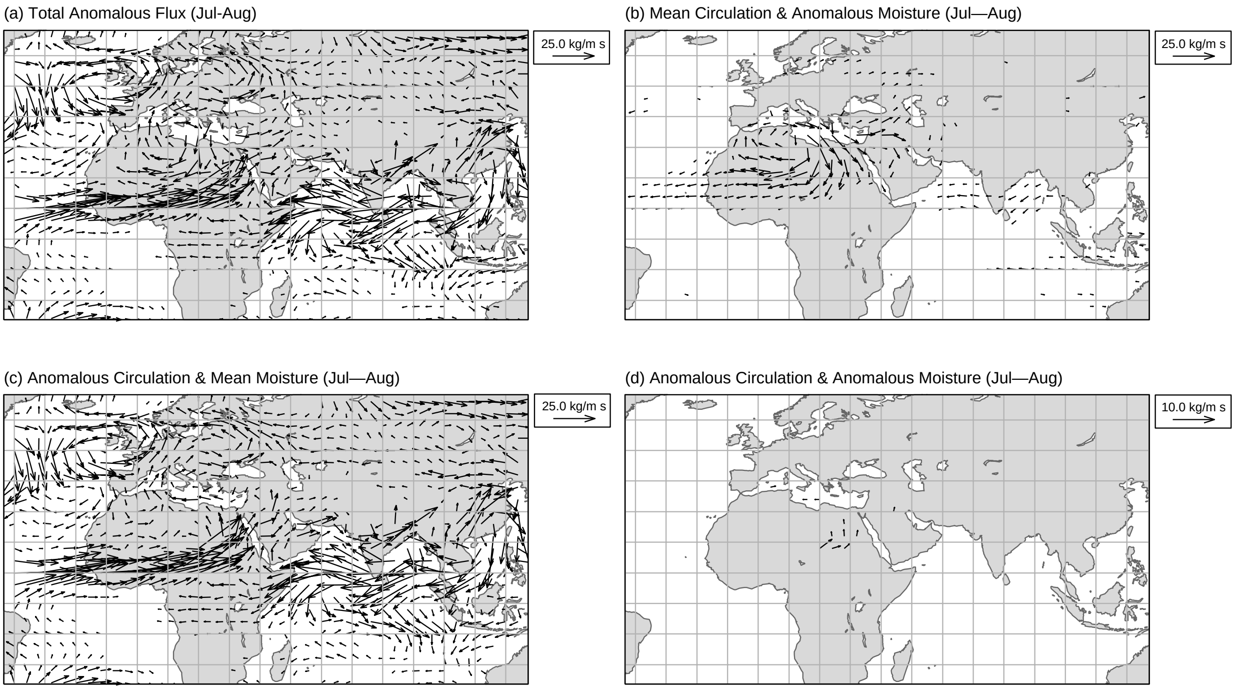

Figure 9: Vertically integrated moisture flux anomalies (MEDOB-CNTL in kg/sm): (a) total anomalous flux along with contributions from (b) anomalous moisture and mean circulation, (c) mean moisture and anomalous circulation, and (d) anomalous moisture and anomalous circulation. Reference arrows are given in the upper right corners.

(Fig. 9b). Thus it is concluded that central influence of the increased sea surface temperatures is their role in increasing humidity, rather than their impact on the dynamical circulation. This result is consistent with the modelling study of Rowell (2003). Relative to the previous two terms, the correlation term $q'\mathbf{v}'$ is insignificant (Fig. 9d). Chou et al. (2001) also point out the importance of low level moisture advection in their idealized study of monsoons.

The analysis of the total anomalous humidity flux was also conducted for experiment MEDAV, in which only the mean SST perturbation is applied. The results are not shown since they closely reproduced the analysis of MEDOB. Thus it appears that spatial arrangement of the Mediterranean SST anomaly in summer 2003 was of minor importance. Given the relatively wide swath of the climatologically stable northerly Harmattan and Etesian winds, one may predict that the relative lack of importance of the SST gradient holds more generally.

4.2 Predictability

From the above discussion it is clear that the link between Mediterranean SST anomalies and Sahel rainfall is a fairly robust feature found in observational data and different atmospheric circulation models. The existence of this link implies some extended-range predictability of Sahel rainfall. To test this conjecture the performance of the operational ECMWF seasonal forecasting system in summer 2003 is examined. (Rowell (2003) briefly discusses the performance of statistical schemes.) The ECMWF seasonal forecast system[2] consists of a 41-member ensemble of coupled ocean-atmosphere simulations at about 210 km horizontal resolution and generates outlooks up to 6 months into the future (see also van Oldenborgh et al., 2006a,b). Ensemble mean anomalies of surface temperature and rainfall as predicted by the coupled ECMWF model for the period

[2] A detailed documentation is available at http://www.ecmwf.int/products/forecasts/seasonal/documentation/.

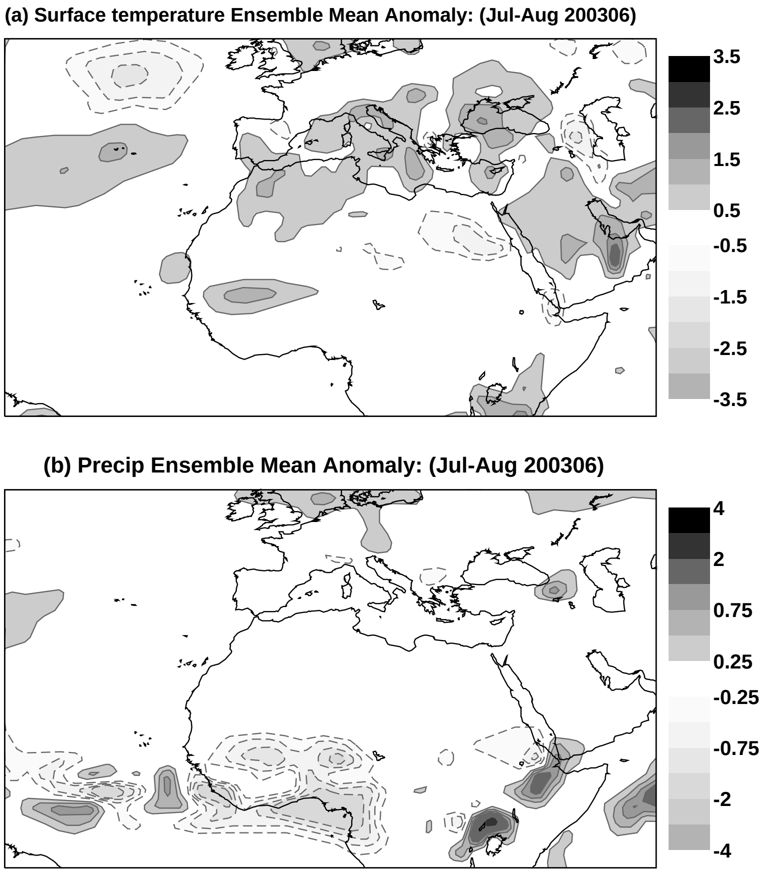

Figure 10: Operational seasonal forecast anomalies for the period July–August 2003: (a) surface temperature (^oC) and (b) precipitation (mm/day). Starting date of the seasonal forecasts is 1 June 2003. Ensemble mean (40 members) anomalies with respect to the model climate are shown.

July–August 2003 are shown in Fig. 10 for the start date of 1 June 2003.

The coupled model appears to show some skill in predicting a warmer than usual Mediterranean sea for the summer season. However, the ensemble mean temperature perturbation is much less than observed at less than 1K everywhere, and with much of the southern eastern part of the Mediterranean basin showing no anomaly exceeding 0.5K at all. Moreover, despite this marginal success at predicting SST, the model shows no skill in simulating increased Sahelian rainfall (Fig. 10b). It is possible that the Mediterranean-Sahel link is too weak for ensemble mean SST anomalies of about 0.5–1 K (Fig. 10a,b) to have a significant impact in the Sahel region. It should also be pointed out in this context that the operational ECMWF seasonal forecasting system uses an older atmospheric model cycle than that used in this study, the former which performs relatively poorly in simulating the north African mean climate due to deficits of the aerosol climatology used (Tompkins et al., 2005; Rodwell and Jung, 2005).

One should be cautious, however, of drawing conclusions about seasonal predictability using only one single case study (summer 2003). To examine the seasonal predictability of Sahel rainfall possibly arising from the Mediterranean-Sahel link for many seasons, hindcasts using operational ECMWF seasonal forecasting system (5 ensemble members) for the period 1987–2003 were analyzed.

The key issue is to determine the predictability of the Mediterranean SST anomalies themselves, since they are the first link in the chain to predict Sahelian rainfall. Anomaly correlations for predicted Mediterranean

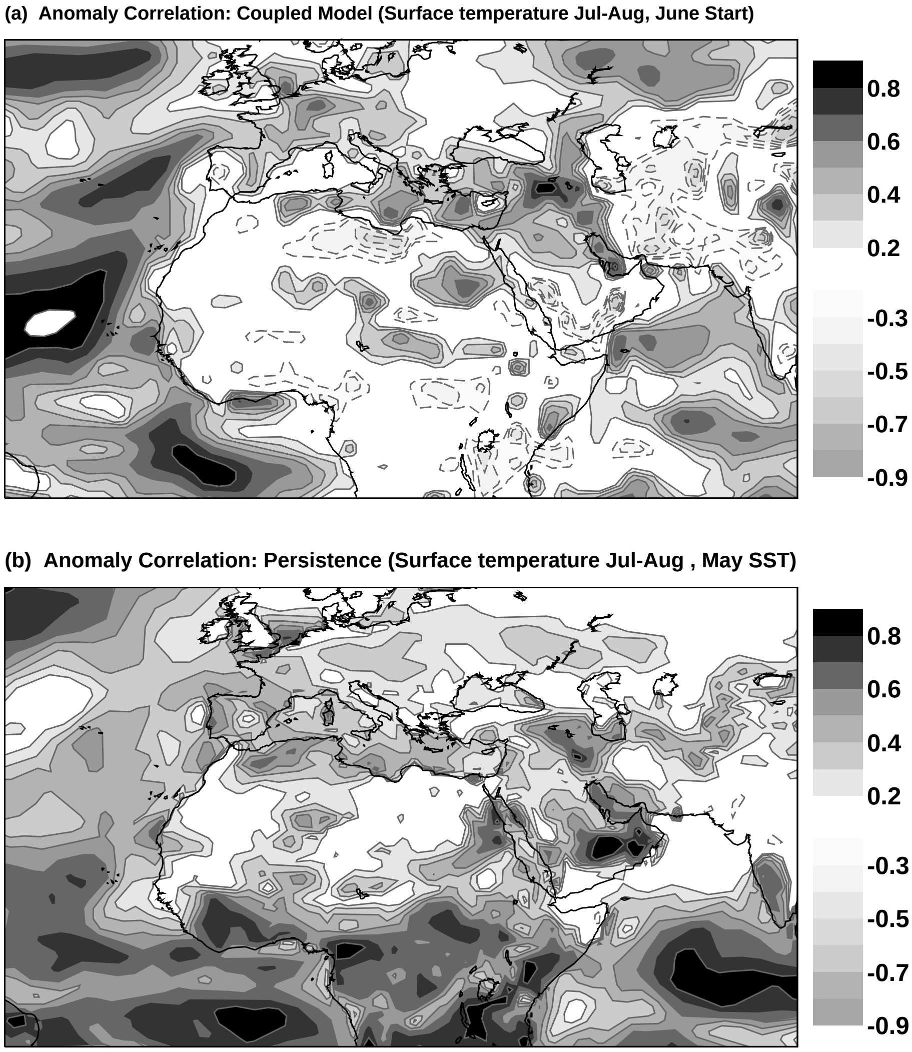

Figure 11: Anomaly correlation coefficients between observed and forecast SST anomalies for the period July–August: (a) ensemble mean forecasts started on 1 June of the years 1987–2003 based on the ECMWF seasonal forecasting system and (b) forecasts based on persisting observed monthly mean SST anomalies from May using data from the period 1958–2001. Ensemble means in (a) are based on 5 members.

ensemble mean surface temperature anomalies[3] for the summer months July–August are shown in Fig. 11 for the start date of 1st June each year.

It appears there is rather weak seasonal predictability of Mediterranean SST anomalies; the anomaly correlation coeffi cients imply that about 10–20% of the observed SST variability during July–August can be predicted by the current operational version of the coupled ECMWF model, though there are some regional differences. However, Fig. 11b reveals that similar levels of skill can be achieved by simply persisting the SST anomalies for the month of May. In other words the skill of coupled model is simply a reflection of the thermal inertia of the ocean. There is also a somewhat surprising lack of predictability of surface temperatures over the land masses relative to the persistence forecast, which merits further investigation.

[3] Surface temperatures over the ocean are equivalent to SSTs.

In order to account for model uncertainty the multi-model dataset provided through the DEMETER project[4] (Palmer et al., 2004) has also been analyzed. Within the DEMETER project 7 different coupled models were run in ensemble mode (9 members each) for the period 1980–2001. Both deterministic and probabilistic forecast skill scores for the multi-model ensemble indicate weak seasonal predictability of summertime Mediterranean SST anomalies (not shown) not unlike that of the ECMWF seasonal forecasting system (see Fig. 11). Moreover, the DEMETER dataset also suggests that the predictability of SST anomalies is larger in eastern part of the Mediterranean. Finally, no indication for any significant seasonal predictability of summertime Sahel rainfall was found in the multi-model ensemble.

This result implies that the high pressure persistent blocking systems, directly responsible for establishing warm Mediterranean SST anomalies (Black et al., 2004), are not predictable much beyond the medium range. Tibaldi and Molteni (1990) found that blocking predictability over Europe dropped dramatically within the range of one week, and more recently Pelly and Hoskins (2003) have shown that there is little predictability in the far medium-range range. However, there is evidence for some predictability of European heat waves in the extended-range (see Rodwell and Doblas-Reyes, 2005, for an overview). Possible sources of predictability encompass, for example, North Atlantic SST anomalies (Rodwell et al., 2004) and interactions of the atmosphere with the underlying soil through soil moisture (Ferranti and Viterbo, 2005). In fact, based on observational data and model experimentation Cassou et al. (2005) even claimed a causal link between the strength of the African Monsoon and decent and associated blocking high pressure over Europe: the reverse mechanism to that suggested by Rowell (2003), indicating a positive feedback may exist. Cassou et al. (2005) also investigated other teleconnections with the conditions in the Caribbean basin and reached a more upbeat conclusion that these teleconnections may lead to improved extended-range predictions of blocking episodes and associated heat-waves over Europe.

In terms of seasonal forecasting it has been found that the Mediterranean-Sahel link is of little practical value. However, it is conceivable that monthly forecasting may benefit, simply because SST anomalies might be more predictable on shorter, sub-seasonal time scales. In fact, an operational monthly forecasting system, which is based on a fully coupled atmosphere-ocean model, has been recently set up at ECMWF (Vitart, 2004). A detailed investigation of the performance of the monthly forecasting system is left to future work.

5 Conclusions

In addition to Mediterranean SST anomalies which considerably exceeded usual interannual variability, the summer of 2003 was marked by record high air temperatures over much of central and Western Europe, and an anomalously wet season in the African Sahel, which stood out against a backdrop of a long term drought in the region. This paper aimed to ascertain if the former could influence the two latter phenomena.

Three months integration were conducted for 45 summer seasons of JJA, with climatological (taken from the ERA-40 reanalysis) SSTs applied everywhere using the ECMWF atmospheric forecast model. In addition to this control, two further experiments were conducted. The first applied the mean Mediterranean SST anomaly observed in 2003 of 2 K uniformly to each of the 45 summer integrations. The second experiment was designed to ascertain if the high order moments of the spatial arrangement of the SST perturbations in the Mediterranean Sea were also important, by instead applying the actual SST anomaly.

The investigation showed that the enhanced SSTs in the Mediterranean has a rather weak, if any, influence on the mid-tropospheric dynamical circulation in Europe, while the rainfall in the Sahel monsoon season is significantly enhanced. Analysis suggests that the increased rainfall was a result of the Rowell (2003) mechanism,

[4]Available at http://www.ecmwf.int/research/demeter/

where the increased SSTs enhance the humidity content of the lower troposphere which is then advected into the ITCZ by the climatological low level flow and results in enhanced deep convection. The analysis conducted here shows that the perturbations to the humidity field caused by the Mediterranean SST anomalies are far more important than the perturbations to the dynamical flow. This finding is different from the mechanism suggested by Raicich et al. (2003), in which a *circulation* change in the eastern Mediterranean (which is remotely forced from anomalies in the Indian summer monsoon) leads to enhanced moisture advection into the Sahel region.

Finally, the results of this study were discussed in terms of seasonal forecasting. It has been pointed out that despite of moderate strength of the Mediterranean-Sahel link the seasonal predictability of summertime Sahel rainfall is absent. This somewhat disappointing result can be partially explained by the fact that the seasonal predictability of Mediterranean SST anomalies—the first part in a chain of processes—is rather weak. From a predictability point of view, thus, the Mediterranean-Sahel link seems to be too weak on seasonal time scales to provide a significant amount of Sahel rainfall skill. Similar conclusions apply to the even weaker Mediterranean-European blocking link.

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