Response to the Summer of 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 the summer of 2003 (July and August) is studied using the European Centre for Medium-Range Weather Forecasts (ECMWF) model. A control integration imposes climatological Mediterranean SSTs as a lower boundary condition. The first sensitivity experiment uniformly increases these Mediterranean SSTs by 2 K, 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 the summer of 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 western European and North Africa continents in three respects. First, 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 the Mediterranean and northwestern Europe were in the 98th percentile of the 1961–90 distribution in 2003, but that in the summer months in particular, warm anomalies exceeded 5 K 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 socioeconomic 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 (SSTs) that were observed over this region. The mean SST anomaly during July–August 2003 amounted to about 2.1 K, with a marked horizontal 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 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) climatology. The peak in SST anomalies is far smaller in the southeastern 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 3 (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 100 mm.

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. The fact that Mediterranean SSTs could have a significant role in the local and nonlocal climate has led to them becoming the focus of a new Climate Variability and Predictability (CLIVAR) subproject: the Mediterranean Climate and Variability and Predictability (MedCLIVAR) project (more information available online at http://www.medclivar.eu/), which among 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, and 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 modeling studies, in which fully controlled experiments can be conducted. From the plethora of possible interactions, this paper aims to use a controlled modeling 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 nonlocal 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 modeling 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 of Rowell (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 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 $T_{159}$ (approximately 1.125° × 1.125°) with 40 levels in the vertical. The performance of earlier model cycles in simulating the observed climate is described elsewhere (e.g., Brankovic and Moltini 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 considered in this study (Tompkins et al. 2005; Rodwell 2005).

In total, three experiments were conducted. A control integration (hereafter termed CNTL) 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 2 K, the approximate average perturbation observed during the 2003 summer season. This experiment is referred to as Mediterranean average anomalies (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 the summer of 2003 are rather small in the eastern Mediterranean Sea; a region which has been identified by Rowell (2003) using observational data as potentially having 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 [the experiment termed Mediterranean observed anomalies (MEDOB)]. The difference between the two sensitivity experiments documents the impact of SST gradients. A summary of the three experiments is given in Table 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 (i.e., 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 the independence of the different experiments from the initial conditions.

3. Results

a. 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 quadruple structure, with the southernmost 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).

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 than in Fig. 2). In both cases the impact of the SST anomaly produces a midlatitude wavelike feature extending from North America toward Europe, not unlike those observed in the summer of 2003 (Fig. 2). The cyclonic and anticyclonic circulation anomalies in the eastern North Atlantic and farther 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 the summer of 2003. It should be noted that in neither experiment are the Z500 anomalies statistically significant 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

![Figure 2](image-url)
results suggest that if summertime Mediterranean SST anomalies have an impact on the atmospheric circulation over Europe, then this impact is 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 northeasterly and southeasterly trade winds in the subtropical Atlantic, the southerly onshore monsoon flow in the Gulf of Guinea, which provides moisture to the African intertropical convergence zone (ITCZ), which attains its northernmost position during this period of the year. The northeasterly 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 westerly monsoon flow to form the elevated dry Saharan air layer (SAL). The strong near-surface northwesterly 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 midtropospheric (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 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 indicates 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 deceleration in both cases. Moreover, it is worth noting that the weakening of the 700-hPa easterly winds extends well into the tropical Atlantic.

b. 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 2-m 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

![Fig. 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.](image-url)
Fig. 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⁻¹) are also given.
Fig. 5. Same as in Fig. 4, except for the 700-hPa level.
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 shortwave 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

Fig. 6. Same as in Fig. 4, except for 2-m air temperature (°C).
observed 2003 SST anomaly in the Mediterranean. The characteristics of deep convection and the monsoon season rainfall are also likely to have been 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 vapor (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 region of North Africa. 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 vapor 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

a. 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: 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 modeling 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 the Sahel, enhancing deep convection there. It seems likely that this is also the case for the simulations conducted here, since increased atmospheric integrated water vapor 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 farther to the west.

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:

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

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

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°N centered along the axis of the ITCZ and the AEJ (Fig. 9a). However, close examination also reveals a significant southerly anomalous humidity flux centered at 20°E, bringing enhanced moist air from the Mediterranean into the deep convective zone. If the subcomponents of the moisture flux are separately examined, these two effects are clearly distinguishable. The westerly anomalous flux along the ITCZ is a result of the deceleration of the climatological easterly low-level and midlevel 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 (Fig. 9b). Thus, it is concluded that central influ-

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ence 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 modeling study of Rowell (2003). Relative to the previous two terms, the correlation term $q'v'$ is insignificant (Fig. 9d). Chou et al. (2001) also point out the importance of low-level moisture advection in their idealized study of monsoons.

Fig. 7. Same as in Fig. 4, except for total precipitation (mm day$^{-1}$).
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 the summer of 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.

b. 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 the summer of 2003 is examined. (Rowell 2003 briefly discusses the performance of statistical schemes.) The ECMWF seasonal forecast system (a detailed documentation is available online at http://www.ecmwf.int/products/forecasts/seasonal/documentation/) 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. 2005a,b). Ensemble mean anomalies of surface temperature and rainfall as predicted by the coupled ECMWF model for the period 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 1 K everywhere, and with much of the southern eastern part of the Mediterranean basin showing no anomaly exceeding 0.5 K 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 (Figs. 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 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 (five 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 ensemble mean surface temperature anomalies\(^1\) for the summer months July–August are shown in Fig. 11 for the start date of 1 June each year.

It appears there is rather weak seasonal predictability of Mediterranean SST anomalies; the anomaly correlation coefficients 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 landmasses relative to the persistence forecast, which merits further investigation.

To account for model uncertainty, the multimodel dataset provided through the Development of a European Multimodel Ensemble System for Seasonal to Interannual Prediction (DEMETER) project (more information available online at http://www.ecmwf.int/research/demeter/; Palmer et al. 2004) has also been analyzed. Within the DEMETER project seven different coupled models were run in ensemble mode (nine

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\(^1\) Surface temperatures over the ocean are equivalent to SSTs.
members each) for the period 1980–2001. Both deterministic and probabilistic forecast skill scores for the multimodel 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 the eastern part of the Mediterranean. Finally, no indication for any significant seasonal predictability of summertime Sahel rainfall was found in the multimodel 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 the blocking predictability over Europe dropped dramatically within the range of 1 week, and more recently Pelly and Hoskins (2003) have shown that there is little predictability in the far medium range. However, there is evidence for some predictability of European heat waves in the extended range (see Rodwell and Doblas-Reyes 2006, 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 2006). 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 descent with associated

Fig. 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 five members.
blocking high pressure over Europe: the reverse mechanism to that suggested by Rowell (2003), indicating that 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 currently of little practical value. However, it is conceivable that monthly forecasting may benefit, simply because SST anomalies might be more predictable on shorter, subseasonal 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 month integrations were conducted for 45 summer seasons of June–August (JJA), with the 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 have a rather weak, if any, influence on the midtropospheric 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, where the increased SSTs enhance the humidity content of the lower troposphere that 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 Raichich 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 the 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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