Teleconnections between the tropical Pacific and the Sahel

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SUMMARY

A greater understanding of equatorial teleconnections is a key aspect of research into seasonal prediction and future climate change for tropical regions. Here the impact of Pacific sea surface temperature (SST) anomalies on rainfall fluctuations over the semi-arid Sahel is explored, using a combination of observed and model data.

The first key topic of this study is the identification of those aspects of anomalous Pacific SST variability that are most strongly linked to the Sahel. One of these, also illuminated by earlier studies, is similar to the classic El Niño Southern Oscillation pattern in the central and east Pacific, which in its El Niño phase increases the likelihood of Sahel drought. It is shown here that, although a part of this link is indirect (operating via Atlantic SSTs), its main effect appears to be through a direct atmospheric teleconnection. The other critical pattern, of equal importance and revealed here by a novel analysis technique, is the large-scale zonal gradient of SSTs from the west Pacific to the east Indian Ocean. If weakened, this too enhances the likelihood of Sahel drought. Atmospheric general circulation model experiments, forced either by observed or idealized SSTs, are used to confirm these two influences on the Sahel. Crucially, their Sahelian impact is substantially reinforced when both are present and, additionally, further empirical analysis shows them to be largely independent.

The second key topic is an investigation of the mechanisms for this Pacific–Sahel teleconnection. These appear to involve anomalous stationary equatorial waves, with communication occurring in both the eastward and westward directions. In El Niño years (for example), a Kelvin wave emanates across the Atlantic from east Pacific convective heating anomalies, and an equatorial Rossby wave appears over the Indian Ocean in response to the anomalous west Pacific–Indian Ocean SST gradients via convective heating anomalies over the Indian Ocean. These interact over Africa to enhance large-scale subsidence over the Sahel, thus reducing seasonal rainfall totals. Irregular changes in propagating equatorial waves or in the residence of subseasonal regimes appear not to play a substantial role.

KEYWORDS: Climate modelling ENSO Sahel SST gradient Tropical teleconnection Equatorial waves

1. INTRODUCTION

At present, teleconnections within the tropics are often poorly understood, yet they are a crucial aspect of past and future climate variability with potentially grave societal impacts. An improved understanding of these phenomena may lead to advances in seasonal prediction and climate change research for tropical regions. An important example, relating features on opposite sides of the globe, is the relationship between sea surface temperatures (SSTs) in the tropical Pacific and seasonal rainfall in the Sahel (e.g. Folland et al. 1991; Rowell et al. 1995, hereafter RFMW; and Janicot et al. 1996). It is an understanding of both the nature and mechanisms of this particular teleconnection that forms the focus of the present study.

Two important issues are explored. First, does this Pacific forcing of Sahel rainfall originate primarily in the east or west Pacific? Second, what are the mechanisms for this teleconnection? Additionally, these questions are linked, in that the origin of the forcing may to some extent determine its direction of influence, i.e. either eastward via the Atlantic, or westward via the Indian Ocean.

Previous studies have often tried to explain such teleconnection mechanisms in terms of fluctuations of ‘Walker-type’ circulations, which are illustrated for example by cross-sections of the divergent flow. However, the trajectory of air parcels is primarily governed by the rotational component of the flow, so that isolating only the divergent component does not reveal genuine overturning motions. An alternative explanation,

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which is pursued here, is that changes to large-scale equatorial waves may link climate variations over the Pacific to those over Africa. Such waves are known to be crucial in determining the mean climatology of the tropical atmosphere (e.g. Gill 1980), and more recently have been proposed as part of the mechanism by which the El Niño Southern Oscillation (ENSO) may affect interannual variations of Atlantic hurricane activity (Jones and Thornicroft 1998).

This study employs a symbiotic combination of observed and model data. First, in section 2 the observed relationships between SSTSs and Sahel rainfall are revisited, including an improved focus on the tropical Pacific and an analysis of the links with large-scale SST gradients. In section 3 this is supported by the analysis of a number of model integrations, which are then used to address the issue of the relative importance of east Pacific versus west Pacific forcing. Subsequent sections then use these model data to describe a mechanism for the teleconnection: in section 4 the relevant aspects of the North African circulation are identified; and in sections 5 and 6 the role of stationary and propagating equatorial waves, respectively, are examined. Finally, a summary and conclusions are presented in section 7.

2. OBSERVED SAHEL–SST RELATIONSHIPS

In this section, we aim to identify the two or three most important features of Pacific SST anomalies that affect observed rainfall totals over the Sahel.

(a) Data

The observed rainfall dataset used in this study is an updated version of that described by Hulme (1994), and utilizes monthly mean rain-gauge records gridded to a resolution of 2.5° latitude by 3.75° longitude. This is identical to the grid of the atmospheric general circulation model (AGCM) employed in later sections. The monthly mean SST dataset is also available on this grid, having been interpolated from the Met Office's 1° reconstruction of global sea-ice and SSTs, GISST3.0 (updated from Rayner et al. 1996).

Almost all the analysis will focus on the July to September (JAS) season, which RFMW and others show to be the months of highest rainfall over the Sahel, and Ward (1998) shows to be months of broadly similar relationships to SSTs. Since rainfall estimates are not always available in some grid boxes, it is stipulated that data must be present in all three months in order to form a seasonal mean.

The period on which the analysis will focus is the 50 years from 1947 to 1996, chosen as it is the longest period over which the quality of rainfall and SST data should be close to its peak. Nevertheless, rainfall–SST relationships during the first half of the century are also briefly studied in subsection 2(e), as well as temporal variations in the strength of relationships throughout the century.

The area defined as the Sahel for this paper encompasses the region 11.25–18.75°N, 16.875°W–35.625°E, which is an eastward extension of the West Sahel region of Thornicroft and Rowell (1998). It is also similar to the definition of RFMW, and to the Central and Southern Sahel regions of Nicholson and Palao (1993). Time series of Sahelian rainfall were created both for observations and for the model by averaging all available grid boxes for each season.

(b) Relationships with global SSTs

In Fig. 1(a), correlations between seasonal Sahel rainfall and SSTs, previously published by Folland et al. (1991), are updated and reviewed. The SST data are retained
on the 2.5° by 3.75° grid, and local significance is tested taking account of serial correlation. The link between variability over the Sahel and ENSO is clearly seen, with El Niño events tending to be associated with drier than average years. However, it is noted that the location of peak correlations is somewhat south of the equator, unlike the canonical ENSO SST pattern of, for example, Rasmusson and Carpenter (1982); this point is explained in subsection 2(c).

Nevertheless, it is clear that ENSO is not the only feature of worldwide SSTs that influences the Sahel, despite being the focus of the current study. The well-known association with the tropical Atlantic (e.g. Lamb 1978; Hastenrath 1990) is also seen,
with warmer than average SSTs in the equatorial and south Atlantic tending to be associated with Sahel drought. Also, warmer than average SSTs in the Indian Ocean tend to be linked with Sahel drought (cf. Palmer 1986, and Shinoda and Kawamura 1994, for example). Conversely, a warming of the eastern Mediterranean is often linked with wetter than average years (cf. RFMW). Significant correlations are also apparent in the extratropical North Atlantic and Pacific, though it is unclear whether this indicates an SST forcing of Sahel rainfall or, perhaps more likely, a link between tropical and extratropical SSTs (cf. Folland et al. 1991).

(c) Relationships with SSTs, excluding the effect of the tropical Atlantic

It is clear from the preceding section, and from other studies, that seasonal anomalies of Sahel rainfall are related to a number of SST patterns around the globe, rather than to any one aspect of SST variability. Since this paper aims to isolate and understand the impact of the tropical Pacific on the Sahel, it will be helpful to explicitly remove the component of rainfall due to the competing influence of the nearby tropical Atlantic. In doing so, it is inherently assumed that where there is covariability of SSTs between these two ocean basins, the 'driving SSTs' are those in the Atlantic since this is nearer the Sahel.

In the past, studies such as RFMW have instead partly isolated the ENSO influence by applying a high-pass filter to the rainfall and SST data. This technique is not employed here because it has the disadvantageous implication that the atmosphere must be aware of the frequency context of the SST anomalies at any given time, and then be able to adopt different responses to each spectral component of the anomaly; this is clearly unphysical. Nevertheless, it can be a useful method for highlighting regions for further investigation, such as the tropical west Pacific; see below.

In this study, in order to exclude the component of Sahelian rainfall due to the nearby tropical Atlantic, an index of the relevant SST anomalies must first be defined. The approach taken here is to use a weighted average of SST anomalies in the area 30°S–30°N, 60°W–20°E, where the weights are each location's relative importance for the Sahel, defined by Fig. 1(a). This time series is then multiplied by –1.0, so that positive values equate to warm anomalies. The JAS Sahel rainfall time series is then regressed onto this index, to provide two orthogonal components of rainfall, one related to tropical Atlantic SSTs and the other related to SSTs elsewhere and/or to chaotic atmospheric dynamics.

First, it is important to record that significant correlations exist between the Atlantic SST index and SSTs in the south-east tropical Pacific (not shown), suggesting that a part of the association between the Pacific and the Sahel is indirect, operating via changes to Atlantic SSTs (cf. e.g. Nicholson 1997, and Sutton et al. 2000). Next, Fig. 1(b) illustrates the associations between the non-Atlantic forced component of JAS Sahel rainfall (noting that this still contains 62% of the variance) and global SSTs. This shows that a significant direct link between ENSO and the Sahel is also likely. Although these Pacific correlations are now lower than those of Fig. 1(a) (having removed the indirect association), with the negative maximum being –0.45, their pattern is now much more like the classic ENSO composite of Rasmussen and Carpenter (1982). Further evidence for a direct impact requires AGCM experiments with anomalous SST forcing; this is addressed in section 3. In the Indian Ocean the pattern of correlations remains widespread, but is barely significant. Again, this may indicate a partly indirect impact, but a significant direct role will also become apparent from the AGCM analysis.
(d) Relationships with SST gradients

Although Fig. 1(b) illustrated a clear link between Sahel rainfall and east Pacific SSTs, it revealed only a weak link with the west Pacific, contrary to RFMW's indicative (but unphysical) analysis of high-pass filtered data. A possible explanation for this disparity is that RFMW's analysis may point to an additional influence from anomalies of large-scale gradients of SST in or around the west Pacific. Moreover, theoretical and simple modelling studies have also shown that changes in the large-scale gradients of SST may have a substantial impact on regional circulation and atmospheric heating patterns (e.g. Lindzen and Nigam 1987). The possibility of such an influence is now explored.

The approach taken here, to compute gradient vectors at a particular spatial scale is first described, using the east–west component as an example. For each grid point, two boxes of the chosen two-dimensional spatial scale are first defined such that the latitudes of their centres are at the same latitude as this grid point, and their longitudes are such that one has its western boundary at the grid point and the other its eastern boundary at the grid point. The difference between their average SSTs (eastern box minus western box) is then computed, and this is divided by the distance between their centres. For each spatial scale this was repeated for all points across the globe, on condition that at least 40% of each box is made up of open water. At all other points the gradient field was set to missing (note that this results in a missing-data mask somewhat different to the usual land–sea mask). These gradients were computed for all years, here using JAS mean data, and representing a broad range of spatial scales: 10° latitude by 20° longitude, 15° by 30°, 20° by 40°, and 30° by 60° (these relative dimensions reflect the greater length-scale of SST anomalies in the zonal direction). Finally, large-scale north–south gradients were also computed in a similar fashion.

In Fig. 1(c), the correlation between the non-Atlantic forced component of Sahel rainfall and east–west SST gradients at a spatial scale of 15° by 30° is shown. Most important is the deep tropics, where two areas of relatively high correlation are apparent: that between the eastern Indian Ocean and the west Pacific (discussed below), and between the east Pacific and the Caribbean. Unfortunately, the latter gradients across Central America cannot be addressed further in this study, as they are not sufficiently well correlated with simulated Sahel rainfall in the GCM available here (subsection 3(b)); further analysis must await a more suitable model. For the subtropics, it is again suggested that significant correlations may only reflect covariability with tropical SSTs, rather than any Sahelian impact (cf. subsection 2(b)). Correlations between Sahel rainfall and large-scale meridional SST gradients were also computed. These are not shown, however, since they reveal no further major links between Pacific SSTs and Sahel rainfall, reflecting only an association with the north–south component of the SST gradient across Central America, and (like Fig. 1(c)) with the borders of the ENSO pattern.

Thus a second key aspect of Pacific SSTs associated with Sahel rainfall is the west Pacific–Indian Ocean SST gradient. This has a peak correlation with the non-Atlantic forced component of Sahel rainfall of 0.52, and so is of similar importance to the actual SSTs in the east Pacific. (Note that the spatial scale of the gradients shown in Fig. 1(c) was chosen to maximize this peak correlation, although the interpretation of this analysis is very similar at other spatial scales.) So a weakening of this large-scale gradient (or slight reversal in extreme years) often, but not always, corresponds to Sahel drought.

A crucial question now is whether these two aspects of Pacific SST variability are actually independent of one another, or whether they simply describe different proxies for ENSO's link with the Sahel. To address this we require an index of SST variability
in each region. For the east Pacific, JAS SST data are averaged over those grid boxes, within the region 15°S–15°N, 180–70°W (excluding the Caribbean), which correlate significantly with the non-Atlantic forced component of Sahel rainfall. (Note that this index correlates with the Niño3 index (i.e. SSTs averaged over 5°N–5°S, 150–90°W) at 0.99 during 1947–96). Similarly, for the west Pacific, SST gradients (on the 15 by 30° scale) are averaged over those grid boxes, within the region 10°S–20°N, 90–130°E, which have significant correlations between SST gradients and rainfall. The correlation between these two time series is computed to be 0.59, indicating that they do indeed have sufficient independence (65% of their variance) such that their impacts on the Sahel should be considered separately. This, and the interaction of these impacts, is discussed further in section 3.

(e) Decadal variations of Sahel–SST relationships

To complete the observational part of this study, the stationarity of these Pacific–Sahel relationships is briefly considered. This is illustrated in Fig. 2, which plots the correlation in a moving 30-year window between the full Sahel rainfall time series and the SST indices defined above.

First, the finding of Janicot et al. (1996, 2001) and Trzaska et al. (1996) is clearly seen, i.e. that Sahel rainfall appears to be more strongly related to east Pacific SSTs in the 1970s and 1980s than during the 1950s and 1960s. Furthermore, Fig. 2 also shows that this relationship was previously strong during the early part of the century, prior to the period analysed by Janicot et al. However, one possible explanation for this decadal variability in strength of interannual relationships, is that it arises merely as an artefact of sampling error. In other words a null hypothesis could be that the ‘signal’ of ENSO’s impact on the Sahel does not vary on decadal time-scales, but that temporal variations in the correlations only occur because of the random effects of ‘atmospheric noise’. To test this, a Monte Carlo approach is used, randomizing the order of the 97 available years and, for each of the resulting 10 000 pairs of Sahel and SST time series, computing a time series of correlations within a moving 30-year window. It is found that for 32% of these correlation time series, the difference between the highest and lowest
points exceeds the same difference computed from the east Pacific curve in Fig. 2. If the correlation window is extended to 60 years, then this difference for the randomized time series exceeds that of the ordered time series on 49% of occasions. Thus, the idea that these decadal variations in the east Pacific–Sahel relationship are simply due to sampling error (and that the underlying population correlation is fixed at a moderate value) cannot be rejected and is, therefore, arguably not worth pursuing further.

Correlations between Sahel rainfall and the west Pacific gradient of SSTs appear from Fig. 2 to be even more stable, and indeed 60% of the randomized correlation time series have a larger range than that shown (22% for a 60-year window). So again, the null hypothesis that this relationship has been stationary throughout the last century cannot be rejected.

Lastly, however, decadal variability in the strength of the well-known relationship between Sahel rainfall and tropical Atlantic SSTs is statistically significant, with only 2% of the randomized correlation time series having a greater range than that shown in Fig. 2 (0% for a 60-year window). This relationship appears to have been non-existent in the early part of the century, and then gradually intensified, reaching its present strength around the 1960s. However, the timing of this peak may arise partly because the Atlantic SST index used here is based on a correlation analysis for 1947–96. Furthermore, Janicot et al. (2001) have deduced a different phasing (during 1945–93 only) to that presented here, by using different SST indices. Nevertheless, this does not affect the first-order result, which is simply that the Atlantic–Sahel relationship is non-stationary (albeit with probable spatial variability of the phasing). For this a number of explanations may be proposed. One is that the variance of the SST pattern (defined by the index described here) may have gradually increased through the twentieth century, so strengthening its link with the Sahel. However, decadal variations of the 30-year standard deviations of the SSTs (not shown) had a different (and statistically insignificant) evolution to that of the correlations, suggesting this idea is not plausible. Another possibility is that this multi-decadal variability may have arisen from errors in the rainfall or SST data, particularly in the early part of the century. However this too seems unlikely, first because Sahelian rainfall relationships with Pacific SSTs were not likewise reduced in the 1900s to 1930s, and second because these multi-decadal variations of Atlantic influence have also been verified against an updated and semi-independent reconstruction of the SSTs (known as HadISST1.1; not shown). The final explanation offered here, and by process of elimination the most probable, is that multi-decadal fluctuations in the underlying basic atmospheric state may have affected (and in this case gradually strengthened) the anomalous mechanisms linking the Atlantic to the Sahel. Presumably this is due to other aspects of the SST field not considered here, and as such demands further analysis, beyond the scope of this study.

3. SIMULATED SAHEL–SST RELATIONSHIPS

(a) The atmospheric general circulation model

The AGCM used in this study to verify and explain the above observational analysis is the HadAM2h version of the Met Office climate model. It has a horizontal resolution of 2.5° latitude by 3.75° longitude, 19 levels in the vertical, and a physics package developed from that of HadCM2 which is described by Johns et al. (1997). These advances in physics are noted by Rowell (1996), who also used the model to analyse interannual to decadal variations of seasonal Sahel rainfall.

Two types of simulation data are described here, both of which are utilized for two main purposes: first to support the observational analysis of a link between two
particular aspects of Pacific SSTs and Sahel rainfall variability; second to understand the mechanisms for these teleconnections. All model data are treated in the same way as the observational data; see subsection 2(a).

(b) Global SST experiments

The first set of experiments consists of an ensemble of simulations forced by the observed history of global SSTs. These aim to simulate past climate variations with maximal skill, providing data with which to verify the model’s mean climate and to add support to the observed relationships between Sahel rainfall and SSTs. Six integrations were carried out, all forced by the GISST3.0 global sea-ice and SST dataset, for the period 1 February 1870 to 30 May 1998. The ensemble members differ only in their initial atmospheric conditions, which were taken from an earlier HadAM2b simulation.

In Fig. 3 the model’s rainfall climatology over North Africa is illustrated for JAS, along with a verification against the gridded observational data. Overall, this aspect of HadAM2b is skillfully reproduced, with the exception of only small negative biases along the southern and western coasts, and a small positive bias in north-east Africa. Averaging rainfall over the Sahel itself also reveals a slight dry bias, with the model climatology being 2.8 mm day$^{-1}$ compared to that observed of 3.5 mm day$^{-1}$. Since rainfall is a zero-bounded field, the interannual variance of Sahel rainfall is also less than observed, although the coefficient of variation is well simulated, being 0.17 for the model, and 0.20 for the observations. Further detail is provided in Table 1 of Rowell (1996).

The skill with which simulated Sahel rainfall responds to global SSTs is illustrated by Fig. 4(a), which shows the correlation between ensemble mean rainfall and worldwide SSTs, for the same period as the observational analysis. The main impression is of much weaker relationships in the simulated data than in the real world. Nevertheless, the pattern of correlations is very similar to that of Fig. 1(a), with Sahel drought tending to be (weakly) related to warmer than average SSTs in the central and east Pacific, the Indian Ocean, and the South and equatorial Atlantic, as well as to cooler than average SSTs in the Mediterranean. Thus the model’s deficiency seems more likely be one of weak signal-to-noise ratios over the Sahel, rather than more serious errors in the
teleconnection mechanisms from distant regions. Indeed Rowell (1996) also reported that a pair of shorter HadAM2b simulations suffered from a relative excess of internal atmospheric variability.

When the component of simulated Sahelian rainfall related to tropical Atlantic SSTs is removed (using the same index as subsection 2(c)), then the correlations of its residual with Pacific and Indian Ocean SSTs is weakened further (Fig. 4(b)). This mirrors the observational analysis, again suggesting that part of the Pacific’s influence on the Sahel is indirect and part is direct. In Fig. 4(c), correlations between the same non-Atlantic forced component of simulated rainfall and the large-scale east–west SST gradients are shown, and these support the pattern of forcing in the west Pacific found in section 2(d). However, a link with large-scale SST gradients across Central America is almost completely absent, suggesting a further model deficiency here.

Finally, an analysis of decadal variability in the strength of these relationships (not shown) also adds weight to the observational results. These show no significant
variations in the strength of impact of east Pacific SSTs or west Pacific SST gradients on simulated Sahelian rainfall, but a significant increase in the impact of the tropical Atlantic (as defined here) from the 1900s to the 1960s.

\[(c)\] Idealized SST experiments

The second type of experimental data consists of a set of integrations forced by idealized patterns of anomalous SST using, in isolation and in combination, the two Pacific features identified in section 2 as being most strongly linked to Sahelian rainfall (west Pacific SST gradients and east Pacific SSTs). These experiments are used to address three important issues. First, we hope to determine whether the Pacific’s forcing of the Sahel arises primarily from just one of these features or from their combination. Note these experiments are not intended to reflect the mechanistic origin of the SSTs (e.g., a tendency for coupling between east and west Pacific), but instead allow an investigation of the particular aspects of ENSO which drive Sahelian rainfall variability, irrespective of their mechanistic origin. Second, they should show a more convincing Sahelian impact than the global SST experiments, because a larger ensemble size is used along with a slightly enhanced, but still realistic, level of forcing. Third, these experiments should also provide a ‘clean’ set of data for mechanistic analysis, since their forcing is restricted to the region of interest and is not simultaneous with forcing from other ocean regions. Three pairs of integrations have been carried out, the details of which are now discussed.

The first pair are forced by anomalous SSTs representing the east Pacific pattern, and are shown by Fig. 5(a) and (b). These depict opposite signs of a single pattern, broadly representing the eastern part of an El Niño event and a La Niña event. The spatial pattern of forcing is designed to be of maximal relevance to the Sahel, and is proportional to a map of the regression coefficients of the observed non-Atlantic-forced component of JAS Sahel rainfall onto SSTs in the central and east Pacific (15°S–15°N, 150°E–70°W). Positive coefficients (in the west) were set to zero, and a linear taper to zero added in the bands 15°–30°N and S. The amplitude of this pattern varies through the annual cycle, such that its size in each month equates to two interannual standard deviations (temporally smoothed with a 1–2–1 filter). This achieves a forcing that is strong in amplitude, but also realistic, with plausible seasonality. These 12 monthly anomaly patterns were then added to (or subtracted from) a seasonally evolving 1961–90 SST climatology, and this single year repeated 20 times. Thus two 20-year integrations were carried out with anomalous forcing in the east Pacific and climatological SSTs elsewhere, in effect creating a pair of 20-member ensembles.

A similar approach was used to derive anomalous SSTs with which to test the impact of the second aspect of Pacific SST variability, the large-scale gradient from the west Pacific to the Indian Ocean. Forcing patterns are shown in Fig. 5(c) and (d). In this case, the pattern was derived by regressing the gradient index, defined in subsection 2(d), onto SST variations in the region 15°S–25°N, 60°–155°E. Coefficients of both signs were retained, and a taper to zero added in a margin extending a further 15° latitude and 30° longitude. Monthly amplitudes were then derived as above, to create an annual cycle of forcing which was applied in two 20-year integrations.

The final pair of integrations were forced with the sum of these east and west Pacific patterns, shown in Fig. 5(e) and (f), to investigate the interaction of their impact on the Sahel. These will be denoted ‘full-ENSO’ experiments.

The remainder of this section describes the tropical precipitation response to these idealized forcings, whereas the circulation changes will be discussed in section 5. Figure 6(a) shows the El Niño minus La Niña composite difference for the east Pacific
Figure 5. Forcing patterns used in the idealized sea surface temperature (SST) experiments: (a) east Pacific El Niño-like experiment; (b) east Pacific La Niña-like experiment; (c) west Pacific SST gradient El Niño-like experiment; (d) west Pacific SST gradient La Niña-like experiment; (e) full ENSO Southern Oscillation (ENSO) El Niño-like experiment; and (f) full ENSO La Niña-like experiment. Averaged from July to September are shown. Contours are plotted at ±0.25, ±0.5, ±1.0, ±1.5 degC, using solid lines for positive values, dashed lines for negative values, and increasing thickness away from zero.

experiments, with the results of a *t*-test for local significance. A strong impact is, not surprisingly, seen over the central and east Pacific, with greater rainfall in the El Niño-like experiment. Regional teleconnections are also apparent, with negative differences over the north-east Pacific warm pool and over the maritime continent, and positive differences over the Philippine Sea and South China Sea. These create atmospheric heating anomalies over the Pacific, which presumably drive the more remote responses. Over the tropical Atlantic this results in a mainly negative response in the El Niño-like experiment and, importantly for this study, a negative response over the Sahel, which is locally significant over the central and eastern Sahel. If this composite difference is averaged over the Sahel box of subsection 2(a), then it demonstrates that HadAM2b does indeed have a clearly significant Sahelian response to Pacific SSTs (at the 2% level), even though its magnitude (−0.28 mm day$^{-1}$) may partly reflect the weak signal-to-noise ratios noted earlier.

In the second pair of ‘partial-ENSO’ experiments, with west Pacific SST gradient forcing, the Pacific response is now much stronger in the western part of the ocean, and weaker in the eastern part (Fig. 6(b)). The response over the Indian Ocean is also unlike that of the east Pacific experiments, with positive differences in the equatorial region and negative differences over the Bay of Bengal. Over the Sahel the response is of the expected negative sign and, being a little smaller than the east Pacific experiment, achieves neither local nor box-average significance.

Finally, in the full-ENSO experiments, the precipitation and atmospheric heating response is equally strong throughout the Pacific region and, not surprisingly, has similar patterns to the partial-ENSO experiments in each of the respective parts of the
tropical Pacific. The resultant response over the Sahel is now much stronger, reaching $-0.71 \text{ mm day}^{-1}$ for the box-average composite difference, and exceeds the 0.1% significance level. Interestingly, this rainfall difference is also significantly greater than that found in either pair of partial-ENSO experiments, indicating that Sahelian rainfall anomalies are most strongly driven by a combination of forcing from both east Pacific SSTs and west Pacific–Indian Ocean SST gradients. This has the important implication that the mechanisms for these distant teleconnections may operate in both the eastward and westward directions from the Pacific to Africa.
4. ENSO-RELATED CIRCULATION CHANGES OVER AFRICA

We can envisage a chain of anomalies linking Pacific SSTs to Sahelian rainfall via, first, convective heating and atmospheric changes over the tropical Pacific and, second, large-scale circulation changes over Africa. This and the following section address the mechanisms for this teleconnection chain, using the wealth of data available in the model integrations described above.

This section focuses on the link between two aspects of this teleconnection chain, by aiming to determine those features of the North African large-scale circulation which are most strongly affected by ENSO. The idea is that reducing the range of possible phenomena over Africa that may link the Pacific to the Sahel will help focus the analysis of section 5, which is aimed at examining the full teleconnection chain. Since it is the strength of relationship that is important here, and since a range of atmospheric variables are to be analysed, a correlation approach is employed. This can only be applied to the long-simulation experiments, which experience a suitable variety of SST forcings in the tropical Pacific. So in Fig. 7 correlations are shown between the east Pacific SST index of subsection 2(d) and a number of features of the African circulation which may potentially form a link in the teleconnection chain. These were chosen where past observational studies showed a possible impact on Sahelian rainfall, and are discussed in turn in the following paragraphs. Where any particular feature is more highly correlated with the Pacific SST index than is the model Sahel rainfall with the same SST index (i.e. correlation coefficient $r > 0.3$), then it is likely that circulation changes over the Pacific first impact this feature of the African circulation, and this then impacts Sahelian rainfall. Thus, we would consider such a feature to be a candidate link in the teleconnection chain, for further consideration in section 5. In these cases, further analysis also confirms that the feature’s correlation with Sahel rainfall is statistically significant (not shown).

Last, it should be noted that Sahelian rainfall may also feedback onto some of these local circulation features, although where the circulation is more strongly correlated with Pacific SSTs than is the rainfall with the SSTs this is unlikely to be the dominant direction of interaction.

Beginning in the upper troposphere, Fig. 7(a) shows that the 200 hPa ‘tropical easterly jet’ (TEJ) (located at about 7°N) is often weakened during El Niño years, with local correlations exceeding 0.5. Given that observational studies show that a weaker TEJ is associated with Sahel drought (Newell and Kidson 1984; Fontaine et al. 1995; though the mechanism is unclear), this feature may, therefore, provide a link between ENSO and the Sahel. Note also the approximate symmetry of the correlation pattern about the equator, which suggests that this may be a stationary Kelvin wave response; this is explored further in section 5.

A second potential influence on Sahelian rainfall may come from the mid-level ‘African easterly jet’ (AEJ), located at about 15°N. Theoretical and numerical studies show this to be crucial for the generation and propagation of squall lines (e.g. Bolton 1984; Weisman et al. 1988) which are the major source of Sahelian rainfall. However, observational analysis suggests that over the Sahel this may not be the main limiting factor for squall line generation (Rowell and Milford 1993) and, additionally, it is unclear whether fluctuations in the AEJ would affect the total amount of convection as well as its organization. On seasonal time-scales, links between the AEJ and rainfall have been found (Newell and Kidson 1984; Fontaine et al. 1995), though these may indicate an influence of rainfall on the AEJ (via soil wetness changes) rather than visa versa. In any case, Fig. 7(b) shows that variations of the AEJ in HadAM2b are not strongly tied to ENSO, with correlations reaching only 0.3 close to its eastern
end (indicating a southward shift of the jet in some El Niño years), and still lower correlations where it crosses the west African coast. Thus, this does not seem a likely candidate for communication of Pacific circulation changes to Sahelian rainfall.

In Fig. 7(c) the impact of ENSO on the activity of African easterly waves (AEWs) is shown, where this is defined as the variance in each JAS season of band-pass (2.5 to 5 days) filtered 850 hPa daily meridional wind data, following Thornicroft and Rowell (1998). This aspect of the regional circulation is also thought by some to affect the generation and propagation of squall lines (e.g. Payne and McGarry 1977), though this may be restricted to the west Sahel where the waves are strongest (see Rowell and Milford 1993; Thornicroft and Rowell 1998). In any case, the simulated AEW activity is no more strongly affected by ENSO than the rainfall itself, and so also seems an unlikely candidate for communication of Pacific SSTs to Sahelian rainfall.

Another possible impact on the likelihood of convection over the Sahel is changes to the large-scale subsidence over North Africa (e.g. Shinoda 1990). This is assessed
here using the low-level height field, which Fig. 7(d) shows to be highly correlated with SSTs in the east Pacific, such that subsidence tends to be enhanced in El Niño years. Although Sahelian convective heating probably feeds back on these subsidence anomalies, the strength of the correlations in Fig. 7(d) suggests that the link with ENSO is primarily from subsidence to rainfall rather than visa versa. Thus, this may be another aspect of the African circulation, besides the TEJ, by which ENSO communicates its influence to the Sahel.

Finally, Fig. 7(e) and (f) show the impact of ENSO on the simulated low-level monsoon flow over North Africa, since both observational and modelling studies show that variations of this moisture supply affect rainfall over the Sahel (e.g. Lamb 1983, Rowell and Milford 1993). A tendency towards a weaker simulated monsoon in El Niño years is indicated by notable negative correlations with the 850 hPa meridional flow across the southern coast of west Africa and the zonal flow near to and east of Lake Chad. A southward shift of the ITCZ is also indicated by positive correlations with the zonal flow along the southern coast of west Africa. (A weakening of the south-westward flow across the Sahara may be related to the enhanced subsidence noted above.) Again, a feedback of Sahelian rainfall probably enhances these anomalies, but the strength of correlations indicates that the ENSO link is more likely to have been initiated by the flow anomalies than by rainfall. Note also that at 925 hPa (not shown) the strength of these relationships is much weaker, indicating that it may be the depth of this layer rather than its entire magnitude that is important (see also Lamb 1983).

This entire correlation analysis has also been repeated using the west Pacific–Indian Ocean SST gradient index. This reveals similar but slightly weaker correlation patterns (not shown), except for a slight reversal in the sign of the relationship with upper-level zonal flow over equatorial east Africa; this is explored further in section 5.

In summary: it appears that Pacific SSTs communicate their Sahelian impact via changes to the strength of the upper-level easterly jet, the large-scale subsidence over North Africa and, to some extent, the low-level monsoon flow. The issue that is now addressed is the mechanism by which these African circulation changes are induced by SST anomalies in the tropical Pacific.

5. A PACIFIC TO AFRICA TELECONNECTION MECHANISM

It was suggested in the introduction that perhaps the most plausible mechanism by which heating anomalies over the tropical Pacific can be communicated to the large-scale flow over Africa is via equatorial waves. Such a teleconnection could either involve changes to the stationary wave response—discussed in this section—or to the propagating wave response—discussed in the following section. To investigate these ideas, data are taken from the idealized SST experiments, which are forced by anomalies that are both consistently large in amplitude and restricted to the region of interest. Analysis focuses primarily on the full-ENSO experiments.

Composites of the El Niño minus La Niña differences, for a number of circulation features, are shown in Fig. 8, with the results of a two-tailed t-test to assess local significance. First, we consider the possibility of a stationary Kelvin wave response. This is clearly illustrated by anomalies of the upper-level zonal flow, whereby Fig. 8(a) shows that a widespread and significant westerly anomaly emanates eastward from the enhanced convective heating over the central east Pacific (see the precipitation changes in Fig. 6(c)). Not surprisingly, this is similar to the way in which simple models respond to tropical heating anomalies, e.g. Gill (1980). These anomalous westerlies extend eastward across the South American continent and the tropical Atlantic, such
that the main wave front is located over the Gulf of Guinea (i.e. where the equatorial anomalies decay to near-zero). An associated area of anomalous subsidence can thus be expected (e.g. Gill 1980), which in this case is concentrated over the north-east tropical Atlantic, the Sahel, the southern Sahara, and the Middle East (Fig. 8(b)). However, this off-equatorial location of these strongest descent anomalies is contrary to Gill's simple modelling study and the more recent aqua-planet study of Neale (1999), both of which find that the largest anomalies are more closely confined to the equator. To understand this further, however, additional experimentation would be required which is beyond the scope of the current study; this could perhaps involve simulations with a number of models having a step-by-step increase in complexity from an aqua-planet to the full AGCM. Even so, one possible explanation is that radiative feedbacks over the Sahara, of the type described by Rodwell and Hoskins (1996), may considerably enhance what would otherwise be only minor anomalies of descent in and around the Sahara. Furthermore, a Rossby wave response over east Africa may also be relevant; see below.

The next stage in the 'teleconnection chain' is the means by which this anomalous subsidence can affect Sahelian precipitation. Two mechanisms may be envisaged. One is that due to the associated adiabatic warming of the free troposphere; convective instability is reduced, and hence so too is precipitation. Second, it can be seen that the anomalous subsidence also increases low-level height and mean-sea-level pressure over the Sahara (Fig. 8(c) and (d)), and that the associated changes in circulation then reduce the moisture flux into the Sahel. The latter is shown by Fig. 8(e), which illustrates a decrease in moisture arriving into the Sahel from the south-west, and also across the southern coast of west Africa from the Gulf of Guinea (see also section 4).

Next, we consider the possibility of a stationary equatorial Rossby wave response to the Pacific heating. This is illustrated in Fig. 8(f) and (g), which use composites of eddy stream function in the upper and lower troposphere (c.f. Kiladis and Wheeler 1995, for example). Most striking is a clear response to the anomalous heating over the central-east Pacific (shown by the precipitation changes in Fig. 6(c)): at upper levels large-scale twin anticyclones appear slightly to the west of the maximum heating, and twin cyclones to the east; at low levels this picture is roughly reversed. However, the zonal extent of this Rossby wave pattern is not sufficient to affect the African continent, consistent with the lower speed of Rossby waves compared to Kelvin waves (e.g. Gill 1980). Nevertheless, a somewhat smaller quadrupole response is also seen over the western Indian Ocean and east Africa. This takes the form of a pair of smaller anticyclones over east Africa, and a less well-defined cyclone pair located to the east (Fig. 8(f)). This is roughly reversed in the lower troposphere (Fig. 8(g)), indicating a baroclinic structure, and is thus broadly consistent with a stationary equatorial Rossby wave forced by convective heating anomalies over the Indian Ocean (the latter shown by Fig. 6(c)). An interesting issue, however, is why a wave number four phenomenon is selected by the stationary response over this region, rather than the wave number two response usually selected over the Pacific; unfortunately a solution to this complex issue is beyond the scope of the current study. The consequence of this response in the upper troposphere is the generation of easterly flow anomalies over equatorial east Africa in El Niño years (Fig. 8(a)). Thus over Africa these meet the westerly anomalies emanating from the east Pacific, and hence appear to play a crucial role in determining the location of the Kelvin wave front and the anomalous subsidence. The entire mechanism is thus summarized in Fig. 9(a) (note that prominent features not relevant to the proposed mechanism are intentionally absent for the sake of clarity). Additionally, this anomalous Rossby wave probably also acts to enhance the anomalous descent over Africa generated by the Kelvin
Figure 8. Composite differences in the full El Niño southern oscillation experiments, computed as averages of 20 El Niño years minus 20 La Niña years, for July to September means of: (a) 200 hPa zonal wind (contours at 0, \pm 2.5, \pm 5, \pm 10, \pm 20 \text{ m s}^{-1}); (b) 500 hPa omega (contours at 0, \pm 0.5, \pm 1, \pm 2 \text{ Pa s}^{-1}); (c) 850 hPa height (contours at 0, \pm 4, \pm 6, \pm 8, \pm 10 \text{ m}); (d) mean sea-level pressure (contours at 0, \pm 0.5, \pm 1, \pm 1.5 \text{ hPa}); (e) magnitude of 850 hPa moisture flux (contour at 0 \text{ g kg}^{-1}\text{m s}^{-1}, and heavy/light shading at \pm 10 \text{ g kg}^{-1}\text{m s}^{-1}); (f) 200 hPa eddy stream function (deviations from the zonal mean; contours at 0, \pm 1, \pm 3, \pm 10 \times 10^{6}\text{m}^2\text{s}^{-1}); and (g) 850 hPa eddy stream function (contours as (f)). Contours are solid lines for positive values, dashed lines for negative values, both with increasing thickness away from zero and a solid line at zero. Local rejection of a null hypothesis of zero difference (at the 5% significance level with a two-tailed test) is indicated by shading in (a) to (d), (f) and (g), and by the addition of moisture flux vectors in (e).
wave and, importantly, may help to explain some of the off-equatorial nature of the precipitation response (c.f. Gill 1980). Furthermore, this mechanism may also illuminate the means by which the Indian Ocean impacts Sahelian rainfall (see Fig. 1(a), and many previous studies), particularly via its gradient to the west Pacific.

Finally, examination of the partial-ENSO experiments also appears to confirm the role played by this anomalous Rossby wave over and to the east of east Africa, and convective heating anomalies over both the Indian and the Pacific Oceans. This
is more easily illustrated by the use of further schematics, shown in Fig. 9(b) and (c). In the experiments forced only by anomalous SSTs in the east Pacific, a similar composite analysis to that above reveals that the anomalous upper-level westerlies extend farther eastward, beyond Africa to the Indian Ocean. This appears to result from the combination of an anomalous Kelvin wave response to the east Pacific convection, and a Rossby wave response, of reverse sign, to reduced convection in the west Pacific (see Fig. 9(b)). (Note that these latter convective anomalies, Fig. 6(a), are themselves a reaction to the enhanced convection in the east Pacific.) This then causes a shift of the strongest area of descent from Africa to the Indian Ocean, where it merges with that over the west Pacific (indicated by the precipitation anomalies in Fig. 6(a)). This can also be viewed as a (partial) cancellation, by the reversed Rossby wave, of the anomalous vertical motion over Africa that would otherwise have been associated with the Kelvin wave. Similarly, in the experiments with anomalous SST gradient forcing in the west Pacific, the upper-level zonal flow anomalies also extend beyond Africa. In this case, shown by Fig. 9(c), these are apparently associated with the combination of a Kelvin wave of reverse sign emanating from reduced convection over the west Pacific, and a Rossby wave over the Indian Ocean associated with locally enhanced convection (Fig. 6(b)). Again, the result is relatively little anomalous descent over Africa.

Thus, this also clarifies the interaction of responses (over the Sahel) to SSTs in both the east and west Pacific, which may be summarized as follows. If one looks at the sign of the major Pacific/Indian Ocean equatorial convective heating anomalies that are first encountered as one moves away from Africa in both the eastward and westward directions, then these must be of the same sign in order to obtain the strongest Sahelian response (c.f. Figs. 6 and 9). If they are of opposite sign, as in the partial-ENSO experiments, then a much weaker response is obtained. This also re-emphasizes that a large Sahelian response is most likely when both features of Pacific SST variability are present, i.e. gradient anomalies from the west Pacific to the Indian Ocean and actual anomalies in the east Pacific.

6. ENSO-RELATED SUBSEASONAL VARIATIONS

Having established the nature and mechanisms of the stationary response over tropical North Africa to ENSO, it is now of interest to examine in greater detail the subseasonal response. Here the focus is on rainfall, and whether events of a particular frequency can become more or less common in response to changes in forcing from the tropical Pacific. This should firstly indicate whether or not there are any changes in the behaviour of equatorial waves which may propagate from the Pacific to Africa, and second whether there could be any changes in the residence probabilities of subseasonal modes fixed in space over Africa. The support or rejection of either of these ideas would then add to our mechanistic understanding of the Pacific to Africa teleconnection. Third, this analysis should also determine whether or not there is any simulated subseasonal response that might have other relevant consequences from an agricultural or societal point of view (e.g. a change in the frequency of dry spells).

To view this frequency dependence of subseasonal rainfall variations, Fig. 10(a) and (b) show the mean spectra of rainfall for the full El Niño and full La Niña experiments, at each longitude along the Sahel (i.e. 15°N), and elsewhere at each longitude along the equator. These were computed using daily rainfall data averaged over three adjacent latitude bands (11.25–18.75°N for 20°W–40°E, and 3.75°S–3.75°N for other longitudes), from which periodograms were derived separately for each longitude and each JAS season. These periodograms were then averaged over the 20 available years,
Figure 10. Longitude–frequency cross-sections of the spectral density of daily rainfall: (a) full El Niño experiment (averaged over 20 years); (b) full La Niña experiment (averaged over 20 years); (c) ratio of full El Niño to full La Niña experiment; (d) as (c), but using spectra from each experiment divided by their own mean spectral density at each longitude. Data from 20°W to 40°E are averaged over 11.25°–18.75°N, and at all other longitudes are averaged over 3.75°S–3.75°N; these regions are separated by white stripes. For periods less than or equal to 30 days July to September data are used; for periods beyond 30 days May to November data are used. Units in (a) and (b) are 10^{-2} mm^2 day^{-2}; asterisks in (c) and (d) indicate the local rejection of a null hypothesis of equal variances (at the 5% significance level with a two-tailed test).

and the resulting longitude–frequency matrix (for each experiment) was smoothed in the frequency domain with a three-point running mean. The main impression of Fig. 10(a) and (b) is not surprisingly that at all longitudes the spectra are dominated by a red noise process. Despite this, a clear enhancement of variability at all frequencies is apparent over the east Pacific in El Niño years compared to La Niña years, associated with the larger mean rainfall here. Similarly a reduction in subseasonal variability is seen over the equatorial west Pacific. Over the Sahel, at 15°N, a small drop in subseasonal variability is also apparent across the frequency range, again consistent with the lower seasonal rainfall in El Niño years.

To illustrate these differences more clearly, and the more subtle changes of other regions, Fig. 10(c) shows the effects of removing the component of the red noise process common to both integrations. This is achieved by plotting the ratio of the spectral densities in El Niño years to those in La Niña years, and highlighting points at which this ratio is locally significant using an $F$-test. However, at many longitudes this is on the same side of unity for all frequencies, indicating that the first-order subseasonal response to ENSO is simply a change in the amplitude of the entire red noise process of the same sign as the change in seasonal mean rainfall. To examine the higher-order effects, Fig. 10(d) shows the spectral ratios between El Niño and La Niña years after their local spectral densities have been scaled by the total spectral density for the
relevant longitude and experiment. Thus, with the effects of the change in amplitude of the red noise spectra also removed from both experiments, any frequency-specific changes in the activity of propagating waves or subseasonal modes should be revealed as a peak or trough in this panel. Local significance was computed using a Monte Carlo approach. Over the east Pacific, low-frequency fluctuations of rainfall (with periods exceeding 20 days) are enhanced beyond the amplification of red noise variability, whereas over the west-central Pacific there is a notable decrease at these frequencies. However, in neither case does there appear to be a link with the Sahel via intermediate longitudes. Over the Sahel itself, Fig. 10(d) shows few significant deviations from unity, providing little evidence for anything other than a change in amplitude of the red-noise process. Thus it seems unlikely that propagating convectively coupled waves or other subseasonal regimes make a substantial contribution to the rainfall fluctuations here. Furthermore, if this response can be confirmed (or refuted) with observational data, it may also provide useful information, for example to the agricultural community, on the interannual behaviour of subseasonal rainfall variations.

7. CONCLUSIONS

This study has been aimed at understanding the boreal summer (July to September) teleconnection between SSTs in the tropical Pacific and rainfall over the Sahel. This may further benefit research into seasonal and climate change prediction for the Sahel (e.g. Colman et al. 1997, Ward 1998, Hulme et al. 2001), and might also aid analysis of other tropical teleconnections. A combination of observed and model data was invaluable, and enabled a dual focus on the aspects of Pacific SST variability that most influence Sahel rainfall and the mechanisms of this influence.

Observational analysis revealed two particular aspects of Pacific SST variability which have roughly equal, and statistically stationary, associations with Sahelian rainfall. One is anomalies of the large-scale gradient of SSTs from the west Pacific to the eastern Indian Ocean, uncovered here for the first time by a new technique designed to assess the impact of such gradients on regional climate anomalies. The second pattern is the classic ENSO signature in the central and east Pacific, revealed by other Sahelian studies. A part of this link was shown here to be indirect, operating via Atlantic SSTs, with the major component being a direct atmospheric impact on the Sahel. These two Pacific patterns are 65% independent, justifying their separate consideration, and indicating that the gradient pattern may be a useful additional predictor of seasonal Sahel rainfall in empirical long-range forecasts.

The impact of these Pacific variations on the Sahel was then supported by a mix of AGCM experiments. First, in simulation mode (with observed SSTs), HadAM2b reproduced the correlations between Sahel rainfall and SSTs, although more weakly than observed. Second, by using specifically designed idealized SST experiments, the Pacific impact on Sahelian rainfall was confirmed, and shown to be strongest only when both ENSO-related patterns are present. These data also provide confidence that the mechanisms of the model teleconnection are probably similar to those of the real world.

Detailed analysis of data from this model led to a proposed mechanism by which ENSO impacts the Sahel, involving teleconnections that operate in both the eastward and westward directions from the Pacific to Africa. First, an anomalous steady Kelvin wave emanates from the region of enhanced convective heating over the central and east Pacific in El Niño years, which at upper levels produces westerly wind anomalies extending across the tropical Atlantic to west Africa. Second, an equatorial Rossby wave response to convective heating anomalies in the Indian Ocean, induced by the
SST gradient anomalies, tends to produce upper-level easterly anomalies over equatorial east Africa. At the juncture of these opposing flow anomalies over Africa, large-scale subsidence is enhanced, particularly over the Sahara and Sahel. One aspect that requires further research is this off-equatorial location of peak subsidence anomalies, although it is speculated that radiative feedbacks over the desert may play an important role. This anomalous subsidence then affects the low-level moisture supply, and presumably the local stability profiles, hence reducing seasonal rainfall totals over the Sahel. The reverse mechanism in La Niña-type years would lead instead to enhanced rainfall over the Sahel.

The additional possibility that propagating waves or other subseasonal modes may play a significant role in this Pacific to Africa teleconnection was rejected here; interannual fluctuations of daily Sahel rainfall were dominated by a change in amplitude of the entire spectrum, with no substantial bias towards any particular frequency. This is in contrast to interannual variations of the Asian summer monsoon, for which Palmer (1994) and Ferranti et al. (1997) suggest that seasonal mean anomalies may be largely determined by shifts in the probability distribution of just one or two subseasonal regimes.

Finally, we recall that the impact of global SSTs on Sahelian rainfall involves the interplay of a number of features besides the Pacific, some of which have been touched on here, and may provide fruitful lines for further research. First, the well-known impact of Atlantic SSTs on the Sahel was shown to be non-stationary; this may be due to multi-decadal variability of the basic state, and clearly demands further research. Second, the tropical Atlantic may also be a crucial part of the global-scale SST pattern known to be linked with the strong multi-decadal variations found in Sahelian rainfall (e.g., Folland et al. 1986, RFMW). Any impact from the extratropical parts of this pattern should also be investigated. Third, a Sahelian impact from Mediterranean SSTs has been supported by the simulation data available here, and this will be discussed in a future paper. Finally, another possible forcing identified here is a link between Sahel rainfall and the large-scale SST gradients across Central America; this too demands further analysis when a more skilful model becomes available.

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REFERENCES

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Lamb, P. J. 1978  Large-scale tropical Atlantic surface circulation patterns associated with sub-Saharan weather anomalies. Tellus, 30, 240–251


