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West African Monsoon Dynamics and Eastern Equatorial Atlantic and Pacific SST Anomalies (1970–88)

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ABSTRACT

The Laboratoire de Météorologie Dynamique atmospheric GCM is used to investigate relationships between West African monsoon dynamics and SST anomalies in the eastern equatorial Atlantic and Pacific for the period 1970–88. Positive SST anomalies in the eastern equatorial Pacific, mainly associated with a larger east–west divergent circulation over the tropical Atlantic, are found to coincide with negative rainfall anomalies over West Africa. This is the case for the composite ENSO warm episodes of 1972, 1976, 1982, and 1983. By contrast, positive SST anomalies in the eastern equatorial Atlantic are accompanied by a southward shift of the intertropical convergence zone along with negative rainfall anomalies in the Sahel and positive rainfall anomalies in the Guinean region. This was the case in 1987. The ENSO warm event during this year had apparently no significant impact on West African monsoon dynamics. A zonal atmospheric coupling associated with differences of SST anomalies between the eastern equatorial Pacific and the Atlantic is evident in the period 1970–88. Positive (negative) phases of this coupling could enhance the impact of ENSO warm (cold) events on West African monsoon dynamics.

1. Introduction

It is well known that connections between northern summer Sahel rainfall and sea surface temperature (SST) anomalies involve the global oceans (Folland et al. 1986; Palmer 1986; Semazzi et al. 1988, 1989; Ward 1992). Statistical relationships are not unique (Rowell et al. 1995): at the interdecadal timescale, the Sahel rainfall is correlated to an interhemispheric SST dipole pattern (a Sahel drought is associated with positive SST anomalies in the Southern Hemisphere and negative ones in the Northern Hemisphere), whereas at the interannual timescale, correlations between Sahel rainfall and SST are stronger on the eastern equatorial Pacific (a Sahel drought is associated with positive Pacific SST anomalies). Janicot et al. (1996) showed that the relationship between SST anomalies and West African rainfall changed after 1970. Between 1945 and 1969, the Sahel rainfall variability was associated with the tropical SST anomaly dipole in the Atlantic (Lamb 1978a,b). After 1970, the correlation between this dipole and Sahel rainfall dropped to an insignificant value, while the correlation between SST anomalies in the eastern equatorial Pacific and Sahel rainfall increased to a highly significant value. In particular, the impact of the El Niño–Southern Oscillation (ENSO) warm episodes seems stronger (Moron et al. 1995).

In this paper, we investigate the role of the tropical divergent atmospheric circulation in connection with the relationship between the West African monsoon and SST anomalies in the eastern equatorial Atlantic and Pacific basins for the period 1970–88. The divergent circulation is diagnosed from model simulation using the Laboratoire de Météorologie Dynamique (LMD) atmospheric general circulation model forced by observed

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global SSTs. Seven integrations, each starting from a different initial condition, were performed using SSTs for the period 1970–88. Those parallel simulations are intended to separate the SST-forced variability from the internal variability of the atmosphere.

We will focus in particular on the relationship between ENSO events and the most recurrent West African rainfall anomaly patterns. Rainfall in West Africa during northern summer is known to exhibit two distinct anomaly patterns (Motha et al. 1980). The first one shows opposite sign rainfall anomalies in the Sahel and in the region to the south. This pattern suggests that the latitude of the intertropical convergence zone (ITCZ) regulates the region of maximum precipitation during the rainy season. The second pattern, characterized by a widespread reduction or increase in rainfall occurring throughout the entire region, is possibly associated with large-scale tropical circulation features. Fontaine and Janicot (1996) showed that the rainfall anomaly patterns documented by Motha et al. (1980) can be associated with different SST anomalies located over the Atlantic and the eastern Pacific.

The datasets and the model experiment for the period 1970–88 are presented in section 2. In section 3, we examine the statistical relationships between equatorial Atlantic and Pacific SST anomalies, focusing first on West African rainfall anomaly patterns and second on simulated tropical divergent circulations. The setup of a zonal atmospheric tropical oscillation is suggested to explain the strong connection between Pacific SSTs and Sahel rainfall on the period 1970–88. A conclusion is given in section 4.

2. Data and methods

a. Rainfall data

Using a monthly rainfall dataset of 110 selected stations regularly distributed in West Africa, Moron (1994) investigated the most recurrent West African rainfall anomaly patterns. He delineated three main coherent regions in summer: the "continental" Sahel, the "western" Sahel, and the "Guinean" region. He derived standardized rainfall indexes based on these regions. Two of them, the continental Sahel rainfall index and the Guinean rainfall index, are described in Fontaine et al. (1995). We define four West African rainfall anomaly types on the period 1970-88, depending on the sign of these two indexes averaged during July-August. Two of them concern in-phase variations over the continental Sahel and the Guinean region. The two others concern out-of-phase variations over these two regions. In-phase rainfall anomaly types will be hereafter refered to as "--" (negative rainfall anomalies over both the continental Sahel and the Guinean region) and "++" (positive rainfall anomalies over both regions). The out-ofphase rainfall anomaly types will be referred to as "-+" ("+-") when negative (positive) rainfall anomalies ex-



FIG. 1. Scatterplot of July–August SST indexes EPAC (abscissa) and EATL (ordinate) from 1970 to 1988 along with occurrences of West African rainfall anomaly types. The rainfall types are displayed only if the absolute value of EATL or EPAC is greater than two-thirds. The rainfall types are indicated by a square for type --, a lozenge for type ++, an upward triangle for type +-, and a downward triangle for type -+. The four rainfall types and the associated rainfall anomaly patterns are displayed below the diagram.

tend over the continental Sahel and positive (negative) rainfall anomalies occur over the Guinean region (see Fig. 1). The types -- and ++ include, respectively, the summers 1972, 1976, 1981, 1982, 1983, 1985, and 1986; and 1974, 1975, and 1980; the types +- and -+ concern, respectively, the summers 1970, 1977, 1978, and 1988; and 1971, 1973, 1979, 1984, and 1987.

b. SST data

SST used in this study originate from monthly analyses provided by the U.K. Meteorological Office (MOHSST4; Bottomley et al. 1990). These data are analyzed on a 5° lat \times 5° long grid and have been corrected for presumed observational bias before 1942. We define two indexes to document variability of SST anomalies during the period 1970–88. The first one (EATL) is the SST average over the eastern equatorial Atlantic ($5^{\circ}N-5^{\circ}S$, $20^{\circ}-5^{\circ}W$). It is well correlated with the leading mode of variability of the tropical Atlantic SSTs (Houghton and Tourre 1992; Zebiak 1993) and describes a large part of SST variability in the Gulf of Guinea, a region above which the monsoon flows before it reaches West Africa. The second one (EPAC) is the SST average over the eastern equatorial Pacific ($5^{\circ}N-5^{\circ}S$, $180^{\circ}-80^{\circ}W$). It is a good indicator of occurrences of ENSO episodes (Deser and Wallace 1990). Each of these indexes is averaged for July–August and standardized anomalies are computed during the period 1970–88.

c. Model description and experimental design

The model used in this study is version 5.0 of the LMD atmospheric general circulation model described in Sadourny and Laval (1984). Its major characteristics are outlined here. The LMD model is a gridpoint model with a standard resolution of 64 points equally spaced in longitude and 50 points equally spaced in the sine of latitude. The vertical coordinate is sigma, the ratio of local pressure to surface pressure. This version has eleven levels: four in the boundary layer, four in the troposphere, and three in the stratosphere. The dynamical processes make use of a lateral diffusion scheme modeled by a mixed bi-Laplacian operator in which the inner part acts on the sigma coordinate and outer parts on the pressure coordinate. The model uses an improved formulation of the solar radiation algorithm of Fouquart and Bonnel (1980), the longwave radiation algorithm of Morcrette (1990), and the interactive cloud-radiation scheme developed by Le Treut and Li (1991). There is no diurnal variation. Moist processes are represented by three condensation schemes: a supersaturation scheme for nonconvective condensation, a moist adiabatic adjustment scheme, and a Kuo scheme for penetrative cumulus convection. Cloud generation is statistically parameterized (Le Treut and Li 1991) and a prognostic scheme has been introduced for the cloud condensed water. In the parameterization of the land surface processes (Laval et al. 1981), the ground surface and the soil moisture are defined for a single layer. Surface albedo is prescribed according to the climatology of Dorman and Sellers (1989). Roughness length z_o is a combination of the climatology of Dorman and Sellers (1989) and of the roughness length used at the European Centre for Medium-Range Weather Forecasts.

A set of seven independent integrations with different initial conditions have been performed on the period 1970–88 using observed global SSTs and sea ice cover. The SST field is a combination of the dataset of Reynolds and Gemmill (1984) for the period 1970–78 and of the Center for Ocean–Land–Atmosphere Studies/Climate Analysis Center AMIP (Atmospheric Model Intercomparison Project) SST and sea-ice dataset for the period 1979–1988 (Gates 1992). More details can be found in Harzallah and Sadourny (1995).

In this paper, computations are based on the sevenmember ensemble average of model outputs, to reduce the effect of internal variability of the model. The statistical significance of correlation coefficients and twotailed Student's t-tests performed in this paper are estimated with regard to the space and time autocorrelations. Detailed explanations of the method followed can be found in Fontaine and Janicot (1992). In addition, Student's t-test statistical significance takes into account internal variability by using the between runs variability to estimate the variance in the t-test statistic.

3. Results

a. Equatorial SST anomalies and rainfall anomaly types

Figure 1 shows the relationships between EATL and EPAC along with the four West African rainfall anomaly types defined for July–August during the period 1970–88. Rainfall anomaly types are displayed in Fig. 1 only when EATL or EPAC is greater than two-thirds in absolute value. This threshold is a compromise between obtaining sufficiently strong SST anomalies and retaining enough cases out of the 19 available.

The correlation between EPAC and EATL indexes is weak (-0.12) during the period 1970–88. This is also true for other periods (Pan and Oort 1990). The combination of these two statistically independent indexes can therefore be considered when analyzing occurrences of different rainfall anomaly types. From Fig. 1 one sees that the rainfall anomaly types -- (1972, 1976, 1982, 1983) are associated with positive EPAC index and with negative EATL index. The types -+ (1973, 1979, 1984, 1987) are characterized by positive EATL index, whatever the sign of EPAC is. Notice, for example, that the summer 1987 is characterized by high positive EATL and EPAC indexes. The remaining rainfall types, ++and +- (1970, 1974, 1975, 1977, 1978, and 1988), are associated mainly with negative EPAC index, whatever the sign of EATL. Also, large positive values of EPAC are accompanied by rainfall types -- except for 1987, and negative EATL index values are associated with above average rainfall in the Sahel when EPAC is negative, and with rainfall type -- when EPAC is positive.

This diagram illustrates the complexity of the relationships between SST anomalies and Sahel rainfall variability for the period 1970–88. In the Gulf of Guinea, for instance, negative SST anomalies occur during abnormally dry as well as during abnormally wet Sahelian rainy seasons. Positive and negative SST anomalies in the Gulf of Guinea can also be associated with the two types of Sahel drought (-+ and --, respectively). The period studied contains two interesting contrasting years, 1987 and 1988. During those two particular years, the Gulf of Guinea was characterized by positive SST anomalies, but 1987 was an ENSO warm event, whereas 1988 was an ENSO cold event. The West African rainfall during these two years was of type -+ and +-, respectively. There is evidently no simple relationship between rainfall over the Sahel and SST in the Gulf of Guinea.

b. Equatorial SST anomalies and simulated tropical atmospheric dynamics

The performance of the atmospheric general circulation model used in this experiment is described in Harzallah and Sadourny (1995). Fields of sea level pressure, 500-hPa geopotential height, precipitation, and winds at 850 and 200 hPa in January and July are realistically simulated by the model. The main deficiencies (underestimations of subtropical high pressures, weak southeast Asian monsoon rainfall in July) are common to major models. Over West Africa, the simulated seasonal cycle of rainfall is realistic. The ITCZ extends too much northward during summer and has a maxima located slightly too north. This discrepancy causes an overestimation of the Sahelian rainy season. The main wind characteristics over West Africa (monsoon flow, easterly and westerly jets in the upper troposphere, vertical wind inside the ITCZ) are also well simulated, except for the African easterly jet in the middle troposphere, which is slightly too weak and is located too far north.

The response of the LMD model to an oceanic forcing was tested in different studies. For example, it was shown that the model simulates realistically the Southern Oscillation atmospheric response to El Niño events, in particular the east–west pressure oscillation and changes in the precipitation. The model was shown to correctly simulate the precipitation over some regional domains, in particular the northeast of Brazil. The links between the variability of precipitation over this region and variability of SST in the Pacific and the Atlantic was studied in detail using the LMD model (Harzallah et al. 1996). It was shown that the LMD model correctly simulates the observed patterns of variability of SST that force the precipitation over the region.

1) VERTICAL MOTION OVER WEST AFRICA

In this section the vertical velocity and its variability associated to SST variation over the two key regions is examined over West Africa using the LMD model. Figure 2a shows the mean simulated vertical velocity (upward for negative values) in July–August (1970–88) averaged over the longitude band $15^{\circ}W-15^{\circ}E$. The vertical velocity was obtained by vertically integrating the continuity equation and applying a divergence correction proportional to its value at each level to obtain a zero-integrated divergence (Krishnamurti 1986). The vertical velocities obtained in this way take into account the vertical motion at each grid point and the divergence field around. Upward motions inside the ITCZ (negative values in Fig. 2a) are well represented with a maximum of 40 hPa day⁻¹ located between 10° and $15^{\circ}N$.



FIG. 2. (a) Latitude–pressure diagram of vertical velocity (dp dt⁻¹) averaged from 15°W to 15°E during July–August 1970–88. Units: hPa day⁻¹. (b) Latitude–pressure diagram of correlations (multiplied by 100) between the EATL index and the vertical velocity averaged from 15°W and 15°E during July–August 1970–1988. (c) Same as in (b) but for the EPAC index. Values for the seven-member ensemble runs are presented. Light/medium/dark gray area indicates correlations significant at the 10%/5%/1% levels, respectively.

We calculated correlation coefficients between the simulated vertical wind field and the EATL index (Fig. 2b). Shaded regions in this figure and in the subsequent ones indicate significant values. Correlations are highly negative and significant between 5° and 15°N, and are particularly strong (up to 0.80 in absolute value) above 500 hPa. Positive SST anomalies in the eastern equatorial Atlantic are therefore strongly associated with enhanced upward motions in the midtroposphere south of 15°N. This is consistent with an increased ascent inside the ITCZ located south of its climatological location. This confirms previous results (Lamb 1978a,b; Hasten-

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FIG. 3. (a) Latitude–pressure diagram of July–August vertical velocity (dp dt⁻¹) averaged from 15° W to 15° E for the composite anomaly of 1972, 1976, 1982, and 1983 related to the 1970–88 mean. Units: hPa day⁻¹. (b) Same as in (a) but for 1987. (c) Same as in (a) but for 1988. Values for the seven-member ensemble runs are presented. Light/dark gray area indicates Student's t-tests significant at the 10%/5% levels, respectively.

rath 1984; Folland et al. 1986; Janicot 1992; Fontaine et al. 1995) and is also in agreement with the occurrences of rainfall anomaly type -+ in Fig. 1.

The correlation pattern calculated between the EPAC index and the simulated vertical velocity (Fig. 2c) is quite different. The figure shows indeed significant positive correlations at the equator and at 15° N (up to +0.60). The simulated ascents are therefore weaker over West Africa during ENSO warm episodes. This is consistent with the occurrence of rainfall type -- in Fig. 1.

An additional way to investigate the association between the vertical velocity and SST indexes is to perform composites. Figure 3a presents the meridional cross section over West Africa of the July–August vertical velocity departures corresponding to the composite ENSO warm event of 1972, 1976, 1982, and 1983. Simulated ascents inside the ITCZ are weaker than average above 700 hPa, and this abnormal subsidence extends toward the equator. No meridional shift of the ITCZ is depicted (not shown). This is consistent with the observed occurrences of rainfall type -- (Fig. 1) and with the simulated rainfall anomalies shown in Janicot (1994). Our composite map agrees with the correlation pattern associated with EPAC (Fig. 2c). We therefore suggest that ENSO warm events had an impact on West African rainfall fields during these summers.

The simulated vertical velocity anomalies for 1987 are shown in Fig. 3b. The ITCZ is enhanced and shifted southward over West Africa. This corresponds to the observed rainfall type -+ (Fig. 1) and is consistent with the simulated rainfall anomalies shown in Janicot (1994). This is also consistent with the correlation pattern associated with EATL (Fig. 2b). Thus we can suggest that in 1987 the impact on West African rainfall field of SST anomalies in eastern equatorial Atlantic was stronger than the possible influence of the ENSO warm episode.

In 1988 the simulated vertical velocity anomaly field over West Africa (Fig. 3c) depicts enhanced ascents above 600 hPa at 15°N, consistent with observed (Fig. 1) and simulated (Janicot 1994) rainfall anomaly fields. This vertical velocity pattern bears some resemblance, with the opposite sign, to the correlation pattern associated with EPAC (Fig. 2c). Thus, it appears that in 1988 the atmospheric circulation over West Africa could be dominated by ENSO cold conditions.

2) EAST-WEST DIVERGENT CIRCULATION OVER THE TROPICAL ATLANTIC

In this section the relationship between the SST anomalies in the eastern equatorial Pacific and the West African monsoon dynamics is analyzed through the east-west divergent circulation. Following Rowell et al. (1992), we computed contours of the vertical integral of July-August simulated zonal divergent mass flux averaged between 5°S and 20°N:

$$\mathrm{MF}(\sigma) = -\frac{a}{g} \int_{-\pi/36}^{\pi/9} \int_{1}^{\sigma} p_{\mathrm{s}} u_{\mathrm{div}} \, d\sigma \, d\lambda,$$

where *a* is the earth's radius (m), *g* the gravity acceleration (m s⁻²), σ the model vertical level, p_s the surface pressure (Pa), u_{div} the zonal divergent wind (m s⁻¹), and λ the latitude (rd).

These contours can be interpreted as streamlines of the zonal divergent flow. For all the results presented here we have verified that the contribution of the zonal divergent mass flux to the vertical velocities is large and that these two quantities can be closely associated. The flow is turning clockwise (counterclockwise) around positive (negative) extrema and its value is proportional to the mass flux gradient. The mean flow is shown in Fig. 4a. The ascending branch located at $150^{\circ}E$ and the subsiding one located over the eastern Pacific point out the Pacific Walker cell. An east–west Atlantic circulation is depicted by its ascending branch located over continental America and its subsiding one located over the longitude band $30^{\circ}W-0^{\circ}$. It is therefore expected that West African rainfall may be influenced by a displacement and/or a variation of the intensity of this Atlantic zonal circulation, as suggested in Janicot (1992).

The composite of zonal divergent mass flux anomalies according to ENSO warm events of 1972, 1976, 1982, and 1983 (July–August) is presented in Fig. 4b. The Atlantic east–west circulation is enhanced, in association with larger ascending motions in the whole troposphere over the eastern Pacific and stronger subsiding motions above 500 hPa over the tropical Atlantic and West Africa. This result is consistent with the previous hypothesis of a connection between these ENSO warm events and droughts over West Africa.

In 1987 (Fig. 4c), the zonal divergent mass flux anomaly field depicts weak negative departure values over the Atlantic. This confirms our suggestion that during this summer the West African rainfall anomaly field was mostly controlled by SST anomalies in the eastern equatorial Atlantic. In 1988 (Fig. 4d), large negative anomalies of zonal divergent mass flux are located over the western part of the tropical Atlantic but do not reach West Africa. We therefore cannot confirm the hypothesis of a direct connection between this ENSO cold episode and West African monsoon dynamics through east–west divergent circulation.

3) PACIFIC-ATLANTIC ZONAL ATMOSPHERIC OSCILLATION

Atmospheric connections between the tropical Pacific and the tropical Atlantic have been examined in various studies. For example, eigenvector analysis performed by Kidson (1975) shows that the equatorial Atlantic zone is part of the large region of variability centered over Indonesia and the western Pacific oscillating with opposite sign to the center located in the eastern Pacific.

An ocean–atmosphere coupling involving the tropical Atlantic and eastern Pacific during northern summer can be described by the difference between EPAC and EATL (Fig. 5a). The correlation field calculated between these values and the simulated mean sea level pressure (Fig. 5b) shows a large zonal dipole between the tropical Atlantic and the eastern part of the tropical Pacific. This zonal oscillation works well when the EPAC–EATL difference is large, as was the case during the ENSO warm events of 1972, 1976, 1982, 1983, or during the cold event of 1988 (Fig. 5a). On the other hand, during summer 1987, the difference between EPAC and EATL was weak. This is consistent with the weak anomalies of east–west divergent circulation over the tropical Atlantic (Fig. 4c).



FIG. 4. (a) Longitude–pressure diagram of vertical integral of the zonal divergent component of mass flux averaged from 20°N to 5°S in July–August 1970–88. Contour interval is 10° kg s⁻¹. (b) Same as in (a) but for the composite anomaly of 1972, 1976, 1982, and 1983 related to the 1970–88 mean. (c) Same as in (b) but for 1987. (d) Same as in (b) but for 1988. Values for the seven-member ensemble runs are presented. Light/medium/dark gray area indicates Student's t-tests significant at the 10%/5%/1% levels, respectively. Arrows indicate the zonal divergent circulation over the tropical Atlantic.



FIG. 5. (a) Time series of the mean July–August difference (EPAC – EATL) index from 1970 to 1988. (b) Correlations (multiplied by 100) between the difference (EPAC – EATL) index and mean sea level pressure for July–August on the period 1970–88. Values for the seven-member ensemble runs are presented.

During the northern summer, when the trade winds and the equatorial oceanic upwelling are well developed in the tropical Atlantic domain, the occurrence of positive SST anomalies in the very eastern part of the equatorial Pacific, similar to the canonical ENSO onset (Rasmusson and Carpenter 1982), can enhance the trade winds over the western Atlantic (Servain and Merle 1993). This would induce an eastward remote dynamical response along the equatorial guideline and the enhancement of the equatorial upwelling in the Gulf of Guinea in a time lag of 1-2 months (Servain et al. 1982; Latif and Barnett 1995). Such a situation is illustrated by the mean July-August simulated 900-hPa zonal wind and SST departures for the composite ENSO warm event of 1972, 1976, 1982, and 1983 (Figs. 6a and 6b). On the other hand, in July-August 1987 (Figs. 6c and 6d), positive SST anomalies are displaced westward in the tropical Pacific. This corresponds to a different pattern that characterizes the mature phase of the canonical ENSO evolution (Rasmusson and Carpenter 1982). No significant variation of the trade winds appears in the western Atlantic as well as no upwelling enhancement in the Gulf of Guinea. One notices that during summer

1987 the easterly component of the harmattan is enhanced over West Africa, which can be associated to the southward retreat of the ITCZ.

4. Conclusions

West African rainfall anomaly types and monsoon dynamics have been examined in connection with two equatorial SST key areas in the eastern parts of Pacific and Atlantic basins. Outputs of seven integrations of the LMD atmospheric general circulation model forced by observed global SSTs for the period 1970-88 have been investigated. This period is characterized by large ENSO warm and cold episodes. The use of ensemble average simulations enables us to extract the impact of SST anomalies on the atmosphere from internal atmospheric dynamics. The extent to which the conclusions of this experiment are model dependent is, of course, an open question although the conclusions from observations and simulations are in close agreement. Other modes of variability of the atmosphere forced by SST centers other than EATL and EPAC may also influence the western African monsoon.

The use of both rainfall indexes in the continental Sahel and Guinean region has been helpful to better differentiate the statistical associations with the EATL and EPAC indexes. SST anomalies in the eastern equatorial Atlantic are linked to the latitudinal location of the ITCZ over West Africa: positive SST anomalies are accompanied by a southward shift of the ITCZ and thus by a drought limited to the Sahel. The east-west divergent circulation over the tropical Atlantic is linked to SST anomalies in the eastern equatorial Pacific and tends to modulate the vertical motion over West Africa. ENSO warm events, when associated with negative SST anomalies in the eastern equatorial Atlantic, are linked to enhanced Atlantic east-west divergent circulation and to decreased upward motions over West Africa, leading to a drought over West Africa. The ENSO warm episode of 1987 seems to have no large impact on West African rainfall. The simulated Atlantic east-west divergent circulation is slightly weaker than average, and the drought, limited to the Sahel, appears to be associated with positive SST anomalies in the eastern equatorial Atlantic and with a southward shift of the ITCZ.

A Pacific–Atlantic zonal atmospheric oscillation is evident in the period 1970–88. It is coupled to the difference of SST anomalies in the eastern equatorial Atlantic and Pacific basins. Janicot et al. (1996) showed that the relationships between SST anomalies and West African rainfall has changed after 1970; in particular,

FIG. 6. (a) July–August zonal component of the wind (positive eastward) at 900 hPa for the composite anomaly of 1972, 1976, 1982, and 1983 related to the 1970–1988 mean. Units: 0.1 m s⁻¹. Light/medium/dark gray area indicates Student's t-tests significant at the 10%/5%/1% levels, respectively. (b) July–August SST anomaly field for the composite of 1972, 1976, 1982, and 1983 related to the 1970–88 mean. Units: 0.1°C. (c) Same as in (a) but for 1987. Light/dark gray area indicates Student's t-tests significant at the 10%/5% levels, respectively. (d) Same as in (b) but for 1987. Values for the seven-member ensemble runs are presented in (a) and (c).



the correlation between SST anomalies in the eastern equatorial Pacific and Sahel rainfall has increased to a highly significant value. The setup of the Pacific–At-lantic zonal atmospheric oscillation, depicted here for the period 1970–88, could be a possible explanation for the strong connection between Pacific SSTs and Sahel rainfall.

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