Impact of Sea Surface Temperature Anomalies on the Atlantic Tropical Storm Activity and West African Rainfall

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ABSTRACT

The association between rainfall over the Sahel and Sudan region and tropical storm activity in the Atlantic is examined using the NCEP–NCAR reanalysis and sea surface temperature anomalies (SSTAs) from 1949 to 1998. Evidence indicates that both are influenced by global SSTAs. The SSTA modes generating favorable atmospheric conditions for tropical storms to develop are also in favor of a wet rainfall season in the Sahel and Sudan region. The easterly waves over West Africa become tropical storms only if the atmospheric conditions over the Atlantic are favorable. These conditions are responses to SSTAs.

In addition to ENSO, a multidecadal trend mode also plays a role. The positive phase of the trend mode features positive loadings in the North Pacific and the North Atlantic, and negative loadings over the three southern oceans. The positive (negative) phases of both modes are associated with increased (reduced) Atlantic tropical storm activity, and with wet (dry) West African monsoon seasons. The SSTAs over the tropical South Atlantic (S-ATL) are related to the rainfall dipole over West Africa, but the influence on tropical storms is not large. Warm (cold) SSTAs over the tropical North Atlantic enhance (suppress) the occurrence of tropical storms, but have little influence on rainfall over West Africa.

The most prominent circulation features associated with the positive phases of SSTA modes are enhanced upper-level 200-hPa easterly winds and reduced vertical wind shear in the main development region of the tropical Atlantic, which are well-known features of active Atlantic tropical storm seasons. The associated low-level flow shows enhanced anomalous westerly winds across the Atlantic to Africa. That allows more moisture transport into Africa and, therefore, more rainfall.

1. Introduction

Landsea and Gray (1992) documented the linkages between Atlantic hurricane activity and rainfall over the Sahel and Sudan region. Later, many studies confirmed that a wet (dry) monsoon season over the western Sahel is usually accompanied by an active (inactive) hurricane season in the Atlantic (Goldenberg and Shapiro 1996; Landsea et al. 1992). Landsea and Gray (1992) suggested that there are two possible mechanisms responsible for the linkages between Atlantic tropical storm activity and West African rainfall: the strengthening of African easterly waves and the large-scale atmospheric anomalies over the North Atlantic.

The easterly wave impacts are important, since approximately 90% of intense hurricanes in the tropical Atlantic are generated from these disturbances (Landsea and Gray 1992). Easterly waves have been studied by Burpee (1972, 1974) and Duvel (1989, 1990). From their work, one can hypothesize that the strength of the easterly waves is related to convective activity over Africa. It has been suggested that strong waves are more likely to become tropical storms or hurricanes (Carlson 1969; Frank 1970). However, not all strong easterly waves develop into tropical storms. A strong easterly wave period does not always coincide with a period of active tropical storms. This suggests that the strength of easterly waves is not the only controlling factor in determining tropical storm activity in the Atlantic.

A host of atmospheric conditions combines to determine either an active or inactive Atlantic tropical storm season, as well as either an exceptional wet or dry Sahel rainfall season will occur. For example, active tropical storm seasons are known to be accompanied by the upper-level easterly wind anomaly and anomalously low vertical wind shear defined as the difference between 200- and 850-hPa zonal winds across the tropical North Atlantic and the Caribbean Sea from 10° to 20°N (Gray 1968; Bender 1997; DeMaria 1996). This area (10°–20°N, 20°–80°W) was labeled as the main development area (MDR) by Goldenberg and Shapiro (1996).

Jones and Thornicroft (1998) suggested that during warm (cold) El Niño–Southern Oscillation (ENSO), the response to rainfall over the Sahel will increase (decrease) the vertical shear over the MDR. Therefore, it

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is unfavorable (favorable) for tropical storms to enhance. However, the relationship between ENSO and rainfall over the Sahel varies from one decade to another (Janicot et al. 1996). There are cases like 1995 and 2000 that active tropical storm seasons were accompanied by normal or below-normal rainfall over the Sahel (Fig. 1b). Therefore, rainfall is one of many factors influencing the tropical storm development.

An alternate theory is that these atmospheric conditions are forced by sea surface temperature anomalies (SSTAs) (Gray 1990). Gray et al. (1997) suggested that the decadal trends of tropical storm activity in the Atlantic are associated with the oceanic circulation. On the interannual timescales, Gray (1984a,b), and Bove et al. (1998) noticed the strong relationship between ENSO and tropical storm activity in the Atlantic. Rowell et al. (1995), Folland et al. (1991), and Ward (1998) related the decadal variations of precipitation over the Sahel and Sudan area to an SSTA mode with negative anomalies over three southern oceans and positive anomalies over the North Pacific and the North Atlantic. The relationship between ENSO and West African rainfall is less straightforward. Janicot et al. (1996) demonstrated that the association between the two was weak in the 1960s and 1970s, but was strengthening after 1970s. Ward (2000), Thiaw et al. (1999), and Janicot et al. (1996) suggested that ENSO contributes to the high-frequency variability of West African rainfall.

In this paper, we suggest that both Atlantic tropical storm activity and West African rainfall are influenced by SSTAs. The SSTA modes in both decadal and interannual timescales that generate favorable atmospheric conditions in the Atlantic for tropical storms to develop also create favorable conditions for a wet monsoon season over the Sahel and Sudan region. The easterly waves become tropical storms only if the
atmospheric conditions over the tropical Atlantic are favorable. These atmospheric conditions are largely influenced by SSTAs. Datasets and procedures used are discussed in section 2. The leading SSTA modes obtained from rotated empirical orthogonal function (REOF) analysis are presented in section 3. The linkages between REOF modes and Atlantic tropical storm activity and West African rainfall are discussed in section 4. The influence of easterly waves is examined in section 5, and conclusions are presented in section 6.

2. Data and procedures

a. Data

The atmospheric circulations are represented by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996). Data are archived on a 2.5° × 2.5° latitude–longitude grid for the period 1949–99. The monthly mean sea surface temperature data were obtained from the reconstruction of historical data based on empirical orthogonal functions (Smith et al. 1996, 1998). These data are archived on a 2° × 2° latitude–longitude grid for the period 1950–96. The precipitation over Africa is represented by the gridded data of monthly precipitation on a 2.75° by 3.75° grid obtained from Dr. Michael Hulme's Web site (Hulme 1991). For monthly mean anomaly fields, the annual cycle was removed by subtracting climatological monthly means from individual monthly means.

The 6-hourly estimated positions and intensities of all Atlantic tropical cyclones from 1949 to 1999 were obtained from the archive at the National Hurricane Center in Miami (Jarvinen et al. 1984). This data period coincides with that of the reanalysis dataset. During this period, the cyclone positions and intensities were augmented by aircraft reconnaissance (Landsea 1993). To verify the easterly waves produced by the reanalysis,
the satellite derived daily infrared (IR) temperature data are used. IR temperatures were obtained from a merge of GOES-8, Meteosat-5, and Meteosat-7 with latitudinally and seasonally dependent zenith angle correlation (Janowiak et al. 2001; Joyce et al. 2001). The resolution is 0.5°, but this dataset is only available from 11 July 1999 to the present.

**b. Procedures**

1) **ROTATED EOF ANALYSIS**

An empirical orthogonal function (EOF) analysis was performed on the seasonal [Aug–Oct(ASO)] mean SSTAs to isolate the leading modes. The ASO means from 1950 to 1996 were used because this is the tropical
storm season (Landsea 1991). To reduce the matrix size, the horizontal grid resolution was reduced to $4^\circ \times 4^\circ$. The anomalies were not normalized and a latitudinal cosine weighting factor was used in computing the covariance matrix. The first 14 EOFs were then subjected to the VARIMAX rotation to obtain REOFs. REOFs do not form an orthogonal set. The correlations between rotated principal components (RPCs) are not zero. The positive phase of all modes coincides with either an active Atlantic tropical storm season or a wet monsoon season over the Sahel. The original time series were then projected onto the REOFs to obtain the corresponding RPCs.

2) RELATIONSHIP BETWEEN SSTA MODES AND THE ATLANTIC NAMED STORM ACTIVITY

To assess the impact of each REOF on the Atlantic tropical storm activity, composites of tropical storm reports were computed based on RPCs. Tropical named storms are defined as cyclones with the maximum sustained surface wind speed greater than 17 m s$^{-1}$ (Landsea 1991; Landsea and Gray 1992). The Atlantic tropical cyclone reports were archived every 6 h. For each year, we obtained the yearly map by counting reports of named storms at each grid point ($1^\circ$ resolution) from August to October. For any given RPC, we then calculated the difference of total tropical storm reports among the 7 highest and 7 lowest RPC years (positive - negative). This difference gives an indication of Atlantic tropical storm activity influenced by that RPC. (The original maps are too noisy. A 9 point smoother was applied to Fig. 5 before plotting.)

The Monte Carlo test was then performed to assess the statistical significance of each difference map. We computed the total difference in named tropical storm reports between 7 pairs of randomly selected yearly maps. The random selection process was then repeated 500 times. The statistical significance of the difference map can be determined from these 500 test cases at each grid point. Field significance was then determined by testing the pattern correlations between the difference map based on the RPC and maps based on randomly selected years (Livezey and Chen 1983). To be statistically significant at the 95% level, there should be fewer than 25 cases (out of 500) in which the pattern correlation between the difference map keyed to a particular RPC and the random test case exceeds 0.23. The statistical significance of the total number of Atlantic tropical storm reports (regardless of location) was also determined for each mode. For the 500 test cases, there is only a 5% chance probability that the difference in tropical storm reports between positive and negative extreme events exceeds 425. Thus, a difference in tropical storm reports exceeding 425 reports between positive and negative extreme RPC events is considered statistically significant at the 95% level.

3. Leading SSTA modes

a. SSTA COMPOSITES

In this paper, we refer to tropical storms and hurricanes collectively as named storms (Landsea and Gray 1992). The seasonal total of named storm days (NSDs) is used to represent tropical storm and hurricane variability (Landsea and Gray 1992). The extratropical storms are not included. A seasonal total of NSDs (Fig. 1a, dark circles) is the amount of days in which a tropical storm (wind speed 18–32 m s$^{-1}$) or a hurricane (wind speed $> 32$ m s$^{-1}$) exists in the Atlantic. If there are two storms during the same day, the count will be 2 days. Another index used is the hurricane destruction potential (HDP) (Fig. 1, open circles). The HDP is defined as the sum of the sustained wind speed squared for every 6 h when a hurricane exists. Two indices are the same as those reported by Gray et al. (1994), and are updated to include recent years. Both indices exhibit decadal
variability, but the decadal trends are most visible in the HDP. Both indices were on average higher during the 1950s and the 1960s, and comparatively low during the 1970–94 period (Gray et al. 1997; Landsea et al. 1996). Thereafter, overall the occurrence of named storms has increased (Goldenberg et al. 2001).

To represent West African rainfall, a West African precipitation (WAP) index was obtained (Fig. 1b) by averaging precipitation over 28 stations (10°–20°N, 20°E–18°W) in the Sahel and Sudan region for July–September (JAS). The raining season there lasts from July to the first week in October. Conclusions will not change if October is added to the mean. The index is given in percentiles obtained based on the gamma distribution determined from data from 1950 to 1999. Consistent with findings of Landsea et al. (1992) and Landsea and Gray (1992), there is a close association between the WAP (Fig. 1b) and the NSD (or HDP) indices on both interannual and the decadal timescales.

To examine the influence of SSTAs on the Atlantic basin storm activity, a composite difference (Fig. 2a) of seasonal mean SSTAs between the 8 most active and 8 least active tropical storm years (active − inactive) based on the NSD index was formed for ASO. The active (inactive) cases correspond to those in which the seasonal total of hurricane days is in the top 85% (lowest 15%) of occurrences. The statistical significance of the composites was determined by the Student’s t-test assuming 1 degree of freedom per year. The composite based on the HDP has the same pattern. Most extreme years based on the NSD are also extreme years for the HDP. Only three events are different. Similarly, the composite difference in SSTAs between the 8 wettest and 8 driest (wettest minus driest) years based on the WAP

Fig. 5. Difference of tropical storm reports between the 7 highest and 7 lowest RPC values based on (a) ENSO mode (RPC 1), (b) S-ATL mode (RPC 3), (c) decadal trends mode (RPC 4), and (d) North Atlantic mode (RPC 10) Contour interval 1 report. Only values that are statistically significant at the 95% level determined by the Monte Carlo test are plotted. Positive values are shaded. A 9-point smoother was applied to the difference maps before plotting.
Fig. 6. Correlation map between precipitation and (a) ENSO mode (RPC 1), (b) S-ATL mode (RPC 3), (c) decadal trend mode (RPC 4) and (d) North Atlantic mode (RPC 10), for JAS. Contour interval is 0.1. Values less than 0.2 are omitted.
index is shown in Fig. 2b. In order to compare with the composite based on the NSD index, Fig. 2b shows the rainfall composite for ASO, but the composite for JAS gives the same pattern.

Overall, two composites (Figs. 2a and 2b) are similar, with positive SSTAs over the North Pacific and the North Atlantic and negative anomalies over the South Atlantic and the western Indian Ocean south of 10°N. In the tropical Pacific, negative anomalies extend across the eastern and central Pacific. The pattern correlation between them is 0.68. The major differences between the two composites are found in the tropical Atlantic. The tropical storm composite features positive anomalies over the tropical North Atlantic and west coast of northern Africa, whereas the composite based on the WAP index features a large area of negative anomalies across the South Atlantic and the equatorial Atlantic. Shapiro and Goldenberg (1998) indicated that active hurricane seasons often feature above-average SSTs across the tropical North Atlantic. For the rainfall composite, the negative SSTAs in the South Atlantic adjacent to Africa (Fig. 2b) are consistent with the analyses of Ward (1998). Despite these regional differences over the Atlantic, the remarkable similarities in the pattern of global SSTAs between the two composites suggest that the same global SSTAs modes may be associated with both Atlantic basin tropical storm activity and West African rainfall. The SSTAs composites can be represented by four rotated EOF modes.

b. SSTAs modes

Only REOFs associated with either or both Atlantic tropical storm activity and West African rainfall are presented here.

1) ENSO mode (REOF 1)

The first REOF mode (Fig. 3a), which is also the first unrotated mode, represents ENSO. It shows negative loadings across the central and eastern tropical Pacific and positive loadings over the western subtropical Pacific. This mode explains 31.8% of the total variance, and will be referred to as the ENSO mode. The positive phase of the mode is associated with active tropical storm seasons. The rotated principal component of the ENSO mode (RPC 1) indicates that the mode was negative during the warm ENSO years of 1957, 1963, 1965, 1969, 1972, 1982, 1987, 1991, 1993, and 1997 (not shown), and positive during the cold ENSO years of 1955, 1956, 1964, 1971, 1973, 1974, 1975, and 1988 (Fig. 4a). The decrease of RPC 1 after 1976 captures the recent warming of SSTAs in the Pacific (Trenberth and Hoar 1996).

2) SOUTH ATLANTIC mode (REOF 3)

The third SSTAs mode (Fig. 3b) explains 7.8% of the total variance, and shows large negative loadings in the South Atlantic. This mode is referred to as the South Atlantic (S-ATL) mode. There is no signal in the Pacific, and it does not relate to ENSO because it resembles the rotated mode REOF 6 obtained by Mestas-Núñez and Enfield (1999) after they had removed the ENSO variability. The RPC for the S-ATL mode (RPC 3; Fig. 4b) exhibits both interannual and interdecadal variability.

3) MULTIDECADAL trends (REOF 4)

The fourth mode (REOF 4) explains 6.8% of the total variance, and shows positive loadings over the extratropical North Pacific and negative loadings in the three southern oceans and in the Coral Sea northeast of Australia (Fig. 3c). This mode will be referred to as the “multidecadal trend mode.” Gray et al. (1997) and Landsea et al. (1999) have related a similar pattern to Atlantic hurricane activity. Gray et al. (1997) have suggested that this pattern is related to the Atlantic conveyor belt through interdecadal changes in the Atlantic thermohaline circulation. REOF 4 is also similar to the 1-point correlation map between low-frequency Sahel and Sudan rainfall anomalies and SSTAs (Rowell et al. 1995). RPC 4 (Fig. 4c) exhibits considerable interdecadal variability, and resembles the low-frequency part of the WAP index (Fig. 1b).

4) NORTH ATLANTIC mode (REOF 10)

The 10th rotated mode (REOF 10) explains 2.1% of the total variance, and shows positive loadings in the tropical and extratropical North Atlantic (Fig. 3d).

4. SSTAs modes and Atlantic tropical storms and West African rainfall

a. Association with Atlantic tropical storm activity

To test the association between each SSTAs mode and Atlantic tropical storm activity, we plotted in Fig. 5 the difference of tropical storm reports between the 7 highest and 7 lowest RPC values.
Fig. 8. Regression map for vertical wind shear of zonal wind anomalies \((u_{200} - u_{850})\) against (a) ENSO mode (RPC 1), (b) S-ATL mode (RPC 3), (c) decadal trend mode (RPC 4), and (d) composite difference map of vertical wind shear for ASO between the 8 most active and 8 most inactive tropical storm seasons based on the NSD index. Contour interval is 0.6 m s\(^{-1}\) (std deviation)\(^{-1}\) for (a)–(c), and 1 m s\(^{-1}\) (std deviation)\(^{-1}\) for (d). Zero contours are omitted. Areas where positive (negative) values are statistically significant at the 95% level are shaded dark (light).
1) ENSO

Figure 5a indicates that cold episodes feature more tropical storms in the western tropical Atlantic, the Caribbean Sea, the Gulf of Mexico, and the western extratropical Atlantic, while warm episodes feature fewer tropical storms in these regions. It is also evident that the ENSO mode (Fig. 5a) is associated with changes in tropical storm activity in the MDR, which extends across the central and western tropical Atlantic and the Caribbean. Active tropical storm seasons often feature significant tropical cyclogenesis in this region, while inactive years can sometimes have no development at all. Our analysis is consistent with Gray (1984a), Saunders et al. (2000). The Pacific cold (warm) episodes are associated with increased (decreased) tropical storm formation in the main development region.

The field significance of this pattern was tested using the pattern correlations. There are only 8 random test cases in 500 whose pattern correlations with Fig. 5a exceed 0.23. The total number of reports in the entire domain regardless the locations of the storms indicates that there are 1350 more storm reports for the positive extreme cases than for the negative ones. Therefore, both measures of field significance indicate that the pattern shown in Fig. 5a is statistically significant at the 95% level.

2) S-ATL MODE

In contrast, the difference in Atlantic tropical storm activity between extremes of the S-ATL mode (Fig. 5b) is only statistically significant over the tropical Atlantic at the 85% level. Thus, this mode is not associated with the dramatic difference in the frequency of tropical cyclogenesis in the main development region, which is a fundamental feature that delineates active and inactive seasons (Goldenberg and Shapiro 1996).

3) DECADAL TRENDS

Over the North Atlantic, the positive phase of the decadal trend mode features more tropical storms along the southeast coast of the United States and in scattered portions of the MDR over the central tropical Atlantic and the Caribbean Sea (Fig. 5c). There are 650 more storm reports for the positive extreme cases than the negative cases. It is statistically significant at the 95% level. Given the low-frequency nature of the trend mode, it is reasonable to suggest that its relationship with Atlantic tropical storm activity is evident primarily on the interdecadal timescales.

4) NORTH ATLANTIC MODE

There are statistically significant differences in tropical storm activity between extreme phases of the mode (Fig. 5d), which is consistent with the findings of Shapiro et al. (2000). Indeed, there are only 2 out of 500 cases in the Monte Carlo test in which the correlations between randomly selected cases and Fig. 5d exceed 0.23. Also, there are 683 more tropical storms for the positive RPC 10 cases than for the negative cases. Each of these calculations indicates that the overall difference in tropical storms between opposite phases of the mode is statistically significant at the 95% level.

Further examination indicates that the positive phase of this mode is associated with more storms over the tropical Atlantic from 20° to 60°W. More storms shift to the area extending north westward toward the United States. The positive phase of the mode also features more storms over the central extratropical North Atlantic. These regions coincide with the well-known tracks of tropical storms that initially form in the main development region.

b. Association with West African rainfall

The correlation between each RPC and seasonal mean (July–September) rainfall anomaly over Africa is given in Fig. 6. The main raining season over the Sahel is July to the first week of October. If ASO is used, results will not change except correlations between RPCs and rainfall are lower. Values greater than 0.32 (0.25) are statistically significant at the 95% (90%) level by assuming 1 degree of freedom per season. If we assume 1 degree of freedom per 2 seasons, then values greater than 0.42 are statistically significant at the 95% level.

For the ENSO mode (Fig. 6a), cold (warm) episodes favor more (less) rainfall between 10° and 17°N including the southern Sahel and the Sudan region. The correlations between RPC 1 and rainfall drop below 0.2 if only data from the early period (1950–76) are used. Most contributions to correlations come from the period after 1976. This decadal change has been reported by Janicot et al. (1996), Thiaw et al. (1999), and Ward (2000). They suggested that ENSO contributes to the high-frequency variations of rainfall. This may explain that investigators (Nicholson and Kim 1997; Janowiak 1988; and many others) using early data periods did not find statistical significant relationship between ENSO and rainfall over the Sahel.

The correlation map between the S-ATL mode and rainfall shows a dipole between rainfall anomalies south and north of 10°N (Fig. 6b). There is no dipole associated with the multidecadal trend mode (Fig. 6c). It only shows positive correlation from 8° to 18°N. There is no significant correlation anywhere between North Atlantic mode (RPC 10) and rainfall over Africa (Fig. 6d). Our results are overall consistent with findings of Fontaine and Janicot (1996). They classified rainfall patterns over West Africa according to the summer rainfall signs in the Sahel and in the Guinean region. The Fontaine and Janicot (−, −) type of rainfall pattern is associated with positive SSTAs over the Pacific and Indian Oceans (their Fig. 1c). That is consistent with the REOF
4 and ENSO modes. Because rainfall over Guinea does not have strong decadal trends, most contributions from trends are from rainfall over the Sahel. For their dipole years (+, − and −, + types), the SSTA composites show anomalies over the tropical South Atlantic including the Gulf of Guinea and SSTAs over the North Atlantic. The association with SSTAs over the Gulf of Guinea is consistent with the S-ATL correlation pattern. We did not find significant correlations with REOF 10. One reason could be that REOF 10 includes SSTAs in both the Tropics and the extratropics. As indicated by Enfield et al. (1999), the Atlantic SST dipole is not one of the REOF modes. This may explain the discrepancy regarding to the SSTAs over the North Atlantic.

We have identified two leading global SSTA modes: the ENSO mode (Fig. 3a) and the multidecadal trend mode (Fig. 3c) associated with variations in Atlantic tropical storm activity and West African rainfall. In addition to these two global modes, the North Atlantic mode (Fig. 3d) is associated with both interannual and interdecadal variations in named storm activity in the MDR, but not with variations in West African rainfall. The S-ATL mode (Fig. 3b) is associated with the dipole rainfall pattern over West Africa, but the influence on tropical storm activity is less important than the two global modes.

5. Atmospheric conditions responsible for the linkages

In this section, we will show that the atmospheric responses to these SSTA modes creating favorable conditions for the Atlantic tropical storms to develop, also are in favor of a wet monsoon season in the Sahel and Sudan. We will concentrate on the multidecadal trend mode and the ENSO mode and discuss the conditions related to the S-ATL. The relationship between SSTAs in the tropical North Atlantic (the N-ATL mode) and hurricanes has already been examined by Shapiro and Goldenberg (1998) and will not be discussed here.

a. Impact on the Atlantic tropical storms

Composite difference maps of 200-hPa eddy streamfunction anomalies with the zonal means removed between the 8 highest and 8 lowest RPCs for all three modes (ENSO, S-ATL, and multidecadal trends) show dipole patterns over both the Atlantic and Pacific basins (Figs. 7a–c). Over the Atlantic, the positive (negative) phase of the modes is associated with positive (negative) streamfunction anomalies in the Northern Hemisphere extending from the tropical Atlantic to the northeastern Africa, and negative (positive) anomalies in the Southern Hemisphere extending westward from the South Atlantic to the southern Africa. A phase reversal in the anomalies is evident over the eastern half of the Pacific basin. These features can also be found in the streamfunction composite difference between active and inactive (active − inactive) Atlantic tropical storm seasons (Fig. 7d). This pattern has been identified by Bell et al. (2000), as the global mode associated with the interannual and interdecadal variations in both Atlantic hurricane activity and West African rainfall.

The streamfunction anomaly pattern associated with the positive phase of each mode is consistent with a strengthening and poleward shift of the upper-level subtropical ridges across the Atlantic, Africa, and the Indian Ocean. These conditions are accompanied by anomalous upper-level easterly winds, anomalous low-level westerly winds, and an amplified tropical upper-tropospheric easterly jet across northern Africa and the equatorial Atlantic, which are well-known features during both active Atlantic tropical storm seasons (Bell et al. 1999, 2000).

One of the most important impacts from this anomalous wind pattern on Atlantic tropical storm activity is through the resulting vertical wind shear over the MDR defined as the difference of the zonal wind between the 200- and 850-hPa levels (u200 − u850 hPa). The vertical wind shear anomalies were regressed against RPCs for the ENSO mode, the S-ATL mode, and the multidecadal trend mode. The regression method allows us to show the relative strength of each mode because the magnitudes of anomalies are displayed proportional to RPC in the unit of its own standard deviation. Areas where values are statistically significant at the 95% level are shaded. The positive (negative) phase of all three modes (Figs. 8a–c) is associated with a large-scale pattern of negative (positive) vertical shear anomalies across the tropical Atlantic and equatorial Africa, which result primarily from the upper-level easterly wind anomalies. The lower-level wind anomalies contribute about 10%–20%. These anomalous vertical shear patterns associated with the ENSO (Fig. 8a) and the multidecadal trend modes (Fig. 8c) extend farthest west to encompass the Caribbean Sea, and resemble the observed composite difference in vertical wind shear between active and inactive named storm seasons (Fig. 8d). The low shear in the MDR is the reason that these two modes are strongly associated with interannual and interdecadal variations in Atlantic tropical storm activity (Figs. 5a and 5c). For the S-ATL mode, the pattern (Fig.

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Fig. 9. (a) The precipitation rate difference between 1998 and 1997 for (JAS) for ENSO (RPC 1), the CAMS-OPI data were used. Contour interval is 1 mm day$^{-1}$, (b) same as (a), but for the composite difference of precipitation rate between the 8 highest and 8 lowest S-ATL (RPC 3) events from reanalysis 6-h forecasts, and (c) same as (b), but for multidecadal trends (RPC 4). Zero contours are omitted. Areas where positive (negative) values are statistically significant at the 95% level are shaded dark (light).
Fig. 10. (a) Vertically integrated moisture fluxes (arrows), and the vertically integrated moisture divergence difference (shaded) between 1998 and 1997 from the reanalysis for ENSO mode (RPC 1), and (b) same as (a), but the difference between the 8 highest and 8 lowest S-ATL mode (RPC 3), and (c) same as (b), but for multidecadal mode (RPC 4). Values greater (less) than 1 mm day$^{-1}$ are shaded dark (light) and the unit vector is 100 kg (ms)$^{-1}$.
8b) is similar, but the magnitudes of negative wind shear anomalies over the MDR are weaker and negative anomalies only extend westward to 50°W. Therefore, the S-ATL mode has impact on the tropical storms only if it is very strong.

b. Influence on West African rainfall

At low level, the atmospheric conditions associated with the positive phase of three modes are strong anomalous lower-level westerly winds extending from the Atlantic to West Africa. To show that, we use the vertically integrated moisture flux. The precipitation rate from the reanalysis was obtained from the 6-h forecasts from the assimilation cycle. Janicot (1999) examined the ability of the reanalysis to depict rainfall over West Africa. He concluded that the reanalysis is able to capture the decadal variations of rainfall, but the decrease of rainfall from 1950 to 1973 depicted by the reanalysis is much higher. After 1974, the assimilated rainfall is more reliable.

The reliability of the vertically integrated moisture fluxes is determined by the ability for the reanalysis to reproduce the correlation patterns between the RPCs and observed rainfall (Fig. 6). The composite rainfall (JAS) difference of the 8 positive and 8 negative RPC extreme events indicates that the reanalysis is able to reproduce the rainfall patterns (Figs. 9b and 9c) consistent with correlations (Fig. 6) for the S-ATL and the multidecadal modes. Both patterns show negative rainfall anomalies over northern Brazil. The reanalysis cannot reproduce the rainfall pattern associated with the ENSO mode (RPC 1). Therefore, we will only show the composite differences of moisture transport for S-ATL and the multidecadal modes. For the ENSO mode, we use the difference between the recent warm event 1997 and the cold event 1998 only as an example. The rainfall difference between these 2 years (Fig. 9a) was obtained from the Climate Anomaly Monitoring System Outgoing longwave radiation Precipitation Index (CAMS-OPI) dataset, which is a global satellite–rain gauge merged product (Janowiak and Xie 1999). It shows positive precipitation anomalies extending from the Atlantic to the area south of 15°N over West Africa consistent with the correlation map (Fig. 6a).

The composite differences of moisture flux and flux divergence between positive and negative RPCs for JAS (Fig. 10) show that the positive phase for all three SSTA modes is associated with strong low-level anomalous westerly transport from the Atlantic to West Africa, which increases the strength of the monsoon circulation and moisture supply to that area. However, the details differ.

For the S-ATL mode (Fig. 10b), there is a dipole pattern of anomalous moisture flux convergence over the Sahel and the Sudan area, with anomalous divergence over Guinea. This supports the precipitation dipole (Figs. 6b and 9b). It is consistent with earlier studies (Ward 1998) indicating that a dipole pattern of anomalous rainfall over West Africa is associated with South
Atlantic SSTAs. For the multidecadal mode, there is no dipole (Fig. 10c). The anomalous westerly flux brings moisture from the Atlantic to West Africa. Anomalous moisture flux convergence covers the area south of 20°N. There is a small area of flux divergence located near the coast of Guinea. Since Fig. 10a is only used as an example, we will not discuss that further. However, anomalous westerly (easterly) winds are common during cold (warm) ENSO years. For example, they also appeared in the 1987–89 ENSO cycle (Palmer et al. 1992).

6. Variability of African easterly waves

To represent African easterly waves, Burpee (1972, 1974) and Duvel (1989, 1990) used the spectral amplitude of the meridional wind at 700 and 850 hPa in the 2.8–5.1-day band. In this study, we use the 2.5–6-day bandpass filtered meridional wind at 850 hPa (V850BP) to examine the interannual variations of these waves. Conclusions will not change if 700-hPa meridional winds are used. Thiaw (1998) demonstrated that the reanalysis is able to simulate easterly waves. Here, the V850BP field is only used to identify periods of strong or weak easterly wave activity. The comparison between the IR temperature and V850BP for 2000 indicates that the reanalysis is able to indicate periods of active and inactive easterly waves.

The IR temperature averaged from 12.5° to 17°N with seasonal mean (1 Jul–30 Oct) removed for summer 2000 is plotted in Fig. 11a. Low values of IR temperature represent convective activity. In the African continent, high values of IR (red) show the diurnal cycle of heating and low IR values indicate diagonally oriented cloud bands propagating westward from 20°E to 20°W. This is consistent with the linkage between increased convective activity and generally stronger easterly waves. The close association between these wave bands and low IR bands suggests that V850BP is a good indicator...
of easterly wave activity. Figure 11b shows that not all waves extend westward into the tropical Atlantic. Some waves extend into the MDR. They match well with low IR values and tropical storm activity. Over the African continent east of 30°CW, the low IR values or the easterly wave activity occurred as often in July 2000 as in the period from 16 August to 15 September. However, there was no named storm in July and there were four named storms in the later period: Chris (17–19 Aug), Debby (19–24 Aug), Ernesto (1–3 Sep), and Helene (15–25 Sep). Climatologically, the vertical wind shear over the MDR is higher in July than in August and September. Therefore, most easterly waves were not able to enhance and develop into tropical storms in July.

Next, we present evidence that the wind shear over the MDR is an important factor to determine whether easterly waves develop into named storms. The IR temperature data are only available for 1999–2000. Therefore, we will use V850BP as an indicator. The satellite data are available after 1979 so we used data from 1979
to 1996. The time longitude diagram of V850BP averaged from 12.5°–17°N for August and September was plotted (not shown) each year. We then selected the 6 most active months (Sep 1981, Sep 1986, Sep 1990, Aug 1993, Aug 1995, and Sep 1995) when many easterly waves were able to extend into the Atlantic west of 30°W. We also selected the 6 most inactive months (Aug 1982, Aug 1983, Sep 1983, Sep 1985, Aug 1989, and Sep 1991) when easterly waves were strong over the African continent (10°W–20°E), but they diminished before reaching 30°W. The mean vertical wind shear for the active and inactive periods (Fig. 12) indicates that the wind shear over the MDR is much higher for the inactive period than the active period.

Our results suggest that strong easterly waves are not predestined to remain large over the tropical Atlantic. There is no direct one to one correspondence between the easterly waves and the development of named storms. The atmospheric conditions over the main development region are also important for storm development. These atmospheric conditions are a part of the much larger scale climate signal influenced by SSTAs.

7. Conclusions

The relationships between West African rainfall and Atlantic tropical storm activity are examined using the reanalysis and SSTAs. Two global SSTA modes, an ENSO mode and a multidecadal trend mode, are shown to be associated with interannual and interdecadal variations in both Atlantic tropical storm activity and rainfall over the Sahel and Sudan. The positive phase of the ENSO mode represents the Pacific cold episode conditions and features negative SSTAs extending from the central to eastern Pacific. The positive phase of the multidecadal trend mode features positive loadings in the North Pacific and the North Atlantic, and negative loadings over the three southern oceans.

Composites or regression maps of various circulation quantities based on the RPCs of SSTA modes establish the accompanying atmospheric circulation features by which the SSTAs ultimately influence Atlantic named storm activity and West African rainfall. One of many prominent circulation features associated with the positive (negative) phases of both the ENSO and multidecadal trend modes is upper-level anticyclonic (cyclonic) circulation anomalies in the subtropical latitudes of both hemispheres, which extend from the Atlantic eastward across Africa toward Australasia. This anomaly pattern is associated with enhanced upper-level easterly (westerly) winds and reduced (enhanced) vertical wind shear of zonal winds in the MDR over the tropical Atlantic, which are well-known features of active Atlantic hurricane seasons.

The atmospheric responses at low level show enhanced (suppressed) anomalous westerly winds across the Atlantic to Africa. The associated moisture flux transports increased (decreased) moisture into the Sahel and Sudan region. The mechanism is similar to the one proposed by Palmer (1986). Rainfall over West Africa is largely controlled by the moisture transport and moisture fluxes associated with large-scale changes in the atmospheric circulation.

Cook and Vizy (1999) demonstrated that the relationship between SSTAs over the South Atlantic is through a positive feedback mechanism. Positive SSTAs enhance evaporation and generate more moist inflow. Therefore, there is more rain over the Guinea. The moisture transport based on the S-ATL modes supports such theory. For cold SSTAs (positive S-ATL mode), there is an increase of moisture transport and anomalous moisture flux convergence over the Sahel region, coupled with a decrease of moisture transport and anomalous moisture flux divergence in Guinea. These conditions contribute to a north–south dipole pattern of rainfall anomalies. The impact on the tropical storm activity is not as strong as the other two global patterns, because the composite of vertical wind shear anomalies related to this mode (Fig. 8b) are weaker. The streamfunction anomalies associated with this mode do have negative anomalies over the tropical North Atlantic, but the center is located over the Sahel.

Jones and Thorncroft (1998) proposed that the vertical shear in the MDR is influenced by West African rainfall and therefore rainfall impacts tropical storm activity during ENSO years. During strong monsoon years over West Africa, positive 200-hPa streamfunction anomalies associated with rainfall may be strong enough to lower wind shear over the MDR. That provides a positive reinforcement of the response to SSTAs. The response to rainfall is mostly local. Their theory does not explain the weak influence of the S-ATL mode on tropical storm activity. The relationship between ENSO and tropical storm activity is strong, but the relationship between ENSO and rainfall changes from one decade to another. There were many active hurricane seasons with normal or below-normal rainfall over West Africa like 1995 or 2000. Therefore, rainfall is not the only controlling factor.

Landsea and Gray (1992) suggested that two possible mechanisms associated with West African rainfall and the Atlantic hurricane activity are the easterly waves and the physical atmospheric conditions. We have shown that not all strong easterly waves originated from West Africa become tropical storms. One of the controlling factors is the vertical wind shear over the MDR. When easterly waves out of West Africa coincide with the period of low vertical shear over the MDR, they are more likely to develop into tropical storms. The wind shear over the MDR is determined by SSTAs.

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