Climatology of Vertical Wind Shear over the Tropical Atlantic

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ABSTRACT

The spatiotemporal variability of the 200–850-hPa vertical wind shear over the tropical Atlantic is examined for a period of 46 yr. This work extends and updates past studies by considering a longer data record as well as a tropospheric-deep measure of vertical wind shear. Composite fields are constructed to illustrate the spatial pattern of the large-scale circulation associated with the mean and extreme cases of vertical shear within the tropical Atlantic. The contemporaneous relationship of vertical shear with El Niño–Southern Oscillation (ENSO) and Sahel precipitation are also examined. While the ENSO–shear correlation appears to have slightly strengthened during the past decade, the Sahel–shear correlation has become significantly degraded.

A combined empirical orthogonal function (EOF) analysis of the zonal and meridional components of the vertical shear reveals interannual and multidecadal modes. The leading EOF exhibits mainly interannual variability and is highly correlated with ENSO. The second EOF is associated with a multidecadal temporal evolution and is correlated with Sahel precipitation. Both EOFs correlate at the same level with tropical cyclones in the main development region of the tropical Atlantic.

1. Introduction

Vertical wind shear is a key environmental variable that controls tropical cyclone development. In general, large values of vertical shear are detrimental to the formation as well as intensification of individual tropical cyclones (e.g., Gray 1968; Zehr 1992; DeMaria 1996; DeMaria et al. 2001). From the standpoint of climate or seasonal-to-interannual prediction, the relevant result from previous studies is that an inverse relationship also exists between large-scale shear and tropical cyclogenesis on seasonal and longer time scales (Gray 1968; Gray et al. 1993). Indeed, several remote predictors in statistical models used to forecast seasonal Atlantic tropical activity appear to influence tropical cyclogenesis by modulating the strength of the vertical shear (Gray et al. 1993; Goldenberg and Shapiro 1996, hereafter GS96). Building on this, Thorncroft and Pytharoulis (2001) have suggested the use of a dynamical approach to seasonal forecasting of tropical cyclones—one that combines predicted vertical shear and statistical relationships gleaned from past associations. Within this context, it is clear that understanding the variability of vertical shear and the factors that influence it are of primary importance.

Previous studies (e.g., Shapiro 1987; Gray 1984; Landsea and Gray 1992; Elsner et al. 1999) have identified several local and remote sources that appear to influence Atlantic tropical cyclone activity. These include the El Niño–Southern Oscillation (ENSO), West African rainfall, Atlantic sea surface temperature (SST), and the quasi-biennial oscillation (QBO). GS96 showed that vertical shear provides a possible dynamical connection between Atlantic hurricane activity and contemporaneous eastern Pacific SST and West African precipitation. Their focus was the main development region (MDR), the area between 10° and 20°N where the majority of Atlantic tropical cyclones form. They found that positive eastern Pacific SST anomalies and negative Sahel rainfall anomalies occur in conjunction with enhanced shear over the MDR via changes in the Walker circulation. GS96 also reported that, compared to the eastern Pacific SST, the Sahel rainfall has a stronger direct impact on the MDR shear.

The results of GS96 raise several issues that require more in-depth investigation. They could only consider...
25 yr of data and were limited to the 700 hPa for their lowest level. The availability of the reanalysis data allows us to examine the long-term climatology of the 200–850-hPa shear, which is more representative of the tropospheric-deep shear experienced by tropical storms. In this study, the longer data record reveals additional information that updates the ENSO–shear and Sahel–shear teleconnections. In particular, we find that during the recent decades, while the association between ENSO and MDR shear has slightly strengthened, the association between Sahel rainfall and MDR shear has significantly weakened.

Another aspect of vertical shear climatology that needs attention is its variability on decadal time scales. There is now sufficient accumulated evidence in the literature that points to multidecadal climate variability in both Tropics and extratropics, with a marked shift in the 1970s. The signal is clearly seen in global SSTs and is reflected in tropical precipitation and key atmospheric indices such as the North Atlantic Oscillation (see Chelliah and Bell 2004 for an overview). Landsea et al. (1999) and Elsner et al. (2000) have highlighted the existence of multidecadal fluctuations in major hurricane activity. Goldenberg et al. (2001) found that the time series of the vertical shear within the MDR is modulated by a multidecadal oscillation. In this study, we provide additional evidence of this multidecadal variability and describe the spatial and temporal structure of this mode.

2. Data and methodology

a. Data sources

This study covers the period 1958–2003. We focus on the months July–October (JASO), thus covering most of the Atlantic hurricane season. Monthly mean zonal and meridional wind fields at the 200- and 850-hPa pressure levels for 1958–2001 are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-Year Re-Analysis dataset (ERA-40). Since the ERA-40 data coverage does not extend beyond August 2002, we supplement the data with the monthly mean ECMWF uninitialized global analyses for the years 2002 and 2003. The wind data are on a 5° latitude–longitude grid. The precipitation data are in the form of anomalies with respect to the period 1961–90 and are stored on a 5° latitude–longitude grid.

The vertical wind shear in this study is defined as the magnitude of the vector difference of the 200- and 850-hPa horizontal winds. We utilize both the zonal and meridional components of the wind field to derive the shear vector for each month. Seasonal values of the magnitude of wind shear are obtained by averaging the monthly fields. All correlations are computed after removing the linear trend from the time series under consideration. Unless otherwise noted, each time series in this study spans 46 yr and correlations between various variables will be deemed significant if their magnitude exceeds the 95% significance level derived from the Student’s t test.

b. Domains

Figure 1 depicts the following domains referred to in this study: the MDR (7.5°–20°N, 85°–15°W); the Niño-3 region (5°S–5°N, 150°–90°W); and the Sahel region (10°–20°N, 20°W–20°E). Figure 1 also shows the genesis locations of all named tropical storms during JASO of 1958–2003. A total of 398 storms are plotted out of which 211 are located within the MDR.

The Niño-3 region is used to represent SST fluctuation associated with ENSO and the Sahel box is used to obtain a measure of West African precipitation. Indices for these domains are computed by averaging the JASO mean data over the respective region for each year. The resulting seasonal mean values are converted into an anomaly time series by removing the mean for the period 1958–2003. Figure 2 shows the indices for Niño-3 SST, Sahel rainfall, and MDR tropical cyclone activity, which will be used in subsequent sections of this paper. It can be seen from Fig. 2 that the Niño-3 SST shows a predominantly interannual variability
while the Sahel rainfall shows both interannual and multidecadal fluctuations. The Sahel rainfall was below average during the 1970s and 1980s but above average during the 1960s and recent years, and this has been well documented in previous studies (e.g., Folland et al. 1986; Ward 1998). The MDR tropical cyclone activity (Fig. 2c) also shows a similar multidecadal variability. This is consistent with Landsea et al. (1999) and Elsner et al. (2000) who found that the Atlantic tropical cyclones, particularly major hurricanes, have varied on a multidecadal time scale.

3. Mean fields

The mean JASO vertical shear for 1958–2003 is shown in Fig. 3. The prominent feature over the tropical Atlantic is the area of strong shear that extends from the Caribbean to northwestern Africa. This area of high shear, with values exceeding 10 m s$^{-1}$, covers a large fraction of the MDR and indicates that the mean shear pattern over the tropical Atlantic is detrimental to tropical cyclone development (Gray et al. 1993). Some of the highest values of vertical shear within the MDR occur over the central Caribbean, a region that is also devoid of tropical cyclone development during the entire period examined here (Fig. 1). The relationship between suppressed tropical cyclone activity and high vertical shear in the Caribbean was recognized soon after upper-air observations from this region became available (e.g., Gray 1968). Figure 3 also depicts the coefficient of variation (CV), defined as the ratio of the standard deviation and the mean JASO shear. Within the MDR, the greatest variability is seen in the western Atlantic, with values as high as 30%. A comparison with the genesis distribution in Fig. 1 indicates that, over the central Caribbean, even a 20% reduction of the vertical shear from its climatological value is not sufficient to bring it within the range conducive for tropical cyclone development.

The spatial pattern of shear in Fig. 3 can be understood by examining the upper- and lower-level circulations deduced from the JASO average streamfunction. The dominant feature in the 200-hPa streamfunction field (Fig. 4a) is the large-scale anticyclone that is centered over the Tibetan Plateau. The axis of the time mean anticyclone shifts southward over the West African monsoon region and extends well into the tropical Atlantic. It can be seen that the characteristic southwest–northeast tilt of the axis of maximum shear in the Atlantic is related to the confluent flow between the western edge of the anticyclone and the mid-Atlantic tropical upper-tropospheric trough (TUTT) located around 40°W.

The 850-hPa streamfunction and the associated circulation can be seen in Fig. 4b. The main feature of interest over the Atlantic is the subtropical anticyclone. The MDR lies within its southern flank and, with the exception of its eastern edge, is entirely characterized by easterly flow at this level. The strong vertical shear seen over the Caribbean (Fig. 3) is related to the presence of a localized low-level easterly jet (Molinari et al. 2000) seen in Fig. 4b. There is evidence in the literature that suggests that the direction of the vertical shear is also a factor in tropical cyclogenesis, with easterly shear being more favorable compared to westerly shear (e.g., Tuleya and Kurihara 1981). From Figs. 4a,b, it can be noted that the mean vertical shear is westerly over the MDR except at around 8°–12°N, off the west coast of Africa, where the low-level southwesterly monsoonal flow and upper-level easterlies contribute to easterly vertical shear. Thus, in a climatological sense, both the magnitude and the direction of vertical shear within the MDR are detrimental to tropical cyclone development.

The annual cycles of the mean MDR vertical shear and the number of tropical cyclones that formed within it are shown in Fig. 5. The mean shear, which is highest during January, decreases through boreal spring and summer, and increases during late fall. August and September, associated with the lowest values of vertical shear, are also the most active in terms of tropical cyclogenesis. Figure 5 also shows that, even though the mean shear during August and September is nearly
identical, there is a substantial increase in tropical cyclone activity in the latter month. This suggests that intraseasonal variability of factors other than vertical shear are also important in determining tropical cyclone development (Shapiro 1987; DeMaria et al. 2001). Possible factors include the variability of precursor disturbances and local SST. It was found by S. Hopsch (2005, personal communication) that the number of coherent disturbances entering the MDR from West Africa is higher in September as compared to August. The SST within the MDR is also higher in September (not shown) and may contribute to the enhanced activity.

4. Vertical shear variability

The time series of JASO shear averaged over the MDR is shown in Fig. 6. Within the record considered here, the mean shear ranges from a maximum of 13 m s$^{-1}$ in 1972 to a minimum of 7.6 m s$^{-1}$ in 1999. The long-term average is about 10 m s$^{-1}$ with a standard deviation of 1 m s$^{-1}$. Also shown in Fig. 6 are the corresponding time series for the 200- and 850-hPa zonal winds. As noted in earlier studies (e.g., GS96), compared to the lower level, the upper-level zonal winds contribute more to the variability of the vertical shear. The zonal winds at these two levels are well correlated ($R = -0.74$). It is also evident that the mean JASO 200-hPa zonal wind can often be negative, indicating net easterly flow within the MDR and consequently substantially lower vertical shear. Many of these years are associated with above average number of tropical cyclones in the MDR (Fig. 2; e.g., 1996 with nine storms and 1961 with eight storms).

a. Relationship with Atlantic tropical cyclone activity

A measure of the relationship between tropical cyclone activity and vertical shear can be gained by comparing the respective time series shown in Figs. 2c and 6. The contemporaneous correlation between the two is $-0.66$, implying that vertical shear can account for as much as 44% of the seasonal tropical cyclone activity within the MDR. Figure 7 illustrates the spatial distribution of the correlations between the tropical cyclone index (Fig. 2c) and vertical shear at each grid point. This chart shows that the correlations over most of the MDR are negative and significant at the 95% level. The correlation within the MDR ranges from $-0.5$ to $-0.7$, corresponding to a reduction of variance on the order of 25%–50%. From Fig. 7 we note that the negative correlation is highest within the Caribbean and central Atlantic. This is broadly consistent with a similar analysis in GS96 that was based on a major hurricane index and the 200–700-hPa vertical wind shear.

While the MDR is mainly characterized by negative correlation between shear and tropical cyclone activity, three regions of positive correlations also stand out in Fig. 7. The zonally oriented region of significant positive correlation in the eastern Pacific reflects the changes in the zonal mean flow associated with the Walker circulation. The second region, over the southeastern United States, corresponds to one of the cen-
terms of the Pacific–North American (PNA) pattern (e.g., Wallace et al. 1993) and indicates a secondary pathway for eastern Pacific SST and Atlantic–shear teleconnection. The correlation in this region, although significant at the 95% level, is relatively weak.

The third region of positive correlation is centered south of the MDR around 30°W and intrudes only slightly within the MDR. One possible mechanism that could link higher shear in this area and elevated tropical cyclone activity in the MDR is West African precipitation. A stronger Atlantic southwesterly monsoon flow will result in higher shear in this particular region but will be associated with greater precipitation over West Africa. Enhanced precipitation over West Africa has been shown to favor tropical cyclone formation by reducing the shear in the MDR (GS96).

b. Spatial patterns for extreme years

It is of interest to examine the spatial patterns of vertical shear during the years with the greatest depa-
ture from its domain averaged value. To illustrate this, we construct composite fields for the five highest (1972, 1983, 1974, 1986, and 1984) and five lowest (1999, 1960, 1963, 1962, and 1981) JASO seasons. The vertical shear in these cases differ from the mean by at least 1.5 times the standard deviation, and thus represents instances of extreme anomalous shear.

The composite for the extreme high shear seasons (Fig. 8a) comprises an elongated positive anomaly that extends along a southwest–northeast tilted axis from the Caribbean to the eastern Atlantic, reaching up to 30°N. The shear over the central MDR is approximately 6 m s⁻¹ higher than the long-term mean. Anomalies of opposite sign are seen in the eastern Pacific as well as to the north and south of the MDR. Of the 28 named tropical storms that formed within the Atlantic during JASO of these years, only 9 (32%) formed within the MDR. Interestingly, of those located within the MDR, 5 formed during 1974. Thus, the picture would have been even more extreme were it not for this “anomalous” year.

The composite for the extreme low shear seasons (Fig. 8b) also has a zonally elongated region of negative anomaly that extends farther westward across Mexico and the southwest United States. In this case, the shear over the central MDR is approximately 4 m s⁻¹ lower than average. Figure 8b also shows the genesis locations of the 38 tropical storms that formed during these five seasons. Of these, 23 (60%) formed within the MDR.

Figure 9 shows the anomalous streamfunction and nondivergent winds at the 200- and 850-hPa levels for the extreme high shear seasons. The prominent feature at the upper level (Fig. 9a) is the large anomalous cyclonic circulation over the tropical North Atlantic basin. This is associated with an amplified mid-Atlantic trough that extends well into the Caribbean. The anomalous upper-level flow over the MDR is westerly, with two distinct local maxima highlighted by the shaded isotach field (Fig. 9a). One lies over the Caribbean and the other over the eastern Atlantic, and both contribute to the high shear within the MDR.

The 850-hPa composite for the extreme high shear seasons (Fig. 9b) shows anomalous anticyclonic circulations over central Atlantic and the southeastern United States. This is a reflection the low-level subtropical anticyclone that is stronger as well as more westward extended, resulting in anomalous low-level easterlies over the central and western MDR. This contributes to the enhanced shear over this region. The results in Fig. 9 indicate that the anomalous circulation associated with the extreme high shear season have significant amplitude both near the equator as well as in the off-equatorial regions of the tropical North Atlantic.

The composite anomaly fields for the extreme low shear seasons are shown in Fig. 10. At the 200-hPa level, the main feature of interest to the MDR shear is an anomalous anticyclone that is located over the central Atlantic (Fig. 10a). The upper-level Tibetan anticyclone is stronger and extends farther into the Atlantic. Consequently, the 200-hPa flow over the MDR is anomalously easterly. The 850-hPa circulation for the low shear composite consists of near-zonal westerly anomalies that are found mostly between the southern flank of the MDR and the equator (Fig. 10b). Over the western MDR, the presence of an anomalous trough leads to northwesterlies that oppose the climatological easterlies in this region. The net effect of the lower- and upper-level anomalies in Fig. 10 is to lower the shear over the MDR.

The composite fields discussed above have high-
lighted the circulation patterns that are associated with extreme departures from the mean shear. The results reveal near-zonal equatorial anomalies, as well as features that have connections to higher latitudes. The importance of subtropical and midlatitude influence on the shear within the MDR is suggested by the anomalous cyclonic and anticyclonic circulations that lie to its north (Figs. 9b and 10b). This may occur through tran-

**Fig. 7.** Correlation between the JASO MDR tropical storm frequency and the JASO 200–850-hPa vertical wind shear. Regions significant at the 95% level are shaded.

**Fig. 8.** Composite mean (contour interval of 2 m s\(^{-1}\)) and anomaly (shaded) of 200–850-hPa shear (m s\(^{-1}\)) for the (a) five highest and (b) five lowest JASO seasons. Initial locations of all JASO tropical storms for the corresponding years are marked by the hurricane symbol.
sient midlatitude synoptic-scale features or through remotely forced stationary waves that may influence the tropical Atlantic via the higher latitudes (e.g., Hoskins and Ambrizzi 1993). The role of the extratropical latitudes within the context of MDR shear variability during the Atlantic hurricane season needs further scrutiny.

c. Relationship with SST and West African precipitation

1) Spatial patterns of correlation

Figure 11a shows the contemporaneous correlations between JASO vertical shear and the ENSO index. The correlation within the MDR is mostly positive with the highest values seen in the western tropical Atlantic. The pattern of statistically significant positive correlation does not cover the entire MDR but instead shifts toward the equator, and joins an extended region of high correlation that stretches from Brazil to eastern Atlantic, between 0° and 10°S. The vectors in Fig. 11a show the structure of the anomalous shear that is associated with an anomalously warm eastern Pacific. It can be seen that the response takes the form of westerly shear that is strongest near the source of the forcing SST. There is also evidence for off-equatorial nonzonal responses such as the positive correlation off the east coast of the United States and a weak cyclonic circulation over the Gulf of Mexico. The pattern in Fig. 11 is consistent with the results of GS96 and implies that anomalously warm conditions over the eastern Pacific are associated with increased vertical shear in the western part of tropical Atlantic.

Figure 11b shows the relationship between JASO Sahel precipitation and vertical shear. The Sahel precipitation is most effective in influencing vertical shear in the central and eastern Atlantic. The pattern of negative correlation shows a southeast–northwest tilt, similar to that seen in earlier figures (e.g., Fig. 3). Other regions of significant correlations that lie outside the MDR are also seen. The region of positive correlation over the southeastern United States, as noted earlier,
corresponds to one of the centers of the PNA and this issue requires additional analysis in order to be understood in the context of the vertical shear–Sahel relationship. Positive correlation can also be seen over eastern Pacific and central Atlantic, south of the MDR. The latter is the same area where positive correlation between MDR tropical cyclones and vertical shear are seen in Fig. 7. This is consistent with the earlier suggestion that higher shear in this region is associated with a stronger monsoon flow, which in turn is associated with wetter Sahel and enhanced MDR tropical cyclone activity. The regressed shear vectors depicted in Fig. 11b follow the southeast–northwest tilt seen in the correlation field. The dominant signal in the vector field clearly lies poleward of 10°N, and is not as equatorially confined as the ENSO response in Fig. 11a. This pattern of association indicates that a wetter-than-normal Sahel induces anomalous easterly shear within the MDR, thus opposing the climatological shear. The general conclusion from Fig. 11 is consistent with that of GS96 although the shear response in the Atlantic is not as equatorially confined in our results.

2) TEMPORAL PATTERNS OF CORRELATION

In this section, we use the simple statistical measure of running correlations to examine whether the strength of the contemporaneous association between MDR vertical shear and eastern Pacific SSTs and West African precipitation has systematically changed over the 46-yr period. This question is motivated by recent studies that have found that the nature of teleconnections related to ENSO has changed over different decades (e.g., Janicot et al. 2001). Additional motivation is also derived from the fact that predictors based on West African precipitation are no longer included in seasonal tropical cyclone predictions made by Gray and coworkers (Klotzbach and Gray 2004) even though earlier studies have documented a strong association between the two (Landsea and Gray 1992).

The result of performing running correlation using consecutive 21-yr segments of Niño-3 index and MDR shear time series is shown in Fig. 12. Also shown in the same figure is the running correlation between the Niño-3 index and MDR tropical cyclone activity.
obtain a measure of the significance of the correlations, 10,000 pairs of synthetic time series were created by randomly ordering each 21-yr segment of the indices and the 95th percentile level of their correlations are plotted in Fig. 12. The correlation between the Niño-3 index and MDR shear appears to steadily increase and become more significant over time although there was a period of reduced correlation centered around the mid-1980s. The anticorrelation between the Niño-3 index and MDR tropical cyclone activity also seems to have increased during the recent period.

The result of the same analysis performed with the Sahel rainfall index is shown in Fig. 13. Compared to eastern Pacific SST, the relationship of the Sahel precipitation is more variable with respect to both MDR shear and tropical cyclone activity. The 1960s and 1970s were associated with strong correlations between Sahel rainfall and MDR shear and tropical cyclone activity. However, the correlations have become significantly degraded since the period centered around the mid-1980s. The variable nature of the relationship between West African precipitation and MDR shear and tropi-

FIG. 11. Charts of correlation (shaded) and regression (vectors, m s\(^{-1}\)) of JASO shear and (a) the Niño-3 index and (b) the Sahel index.

FIG. 12. Running correlations using consecutive 21-yr segments between the JASO Niño-3 index and MDR shear (solid line) and between the JASO Niño-3 index and MDR tropical cyclone frequency (dashed line). The thin dashed lines represent the 95th percentile level of ranked correlations between 10,000 pairs of synthetic time series constructed by randomly ordering the respective indices.
cal cyclone activity offers a perspective different from past studies (e.g., Landsea and Gray 1992; GS96) that examined shorter time periods. The result, however, needs to be viewed with caution since the period of this study is limited. Further work is needed to determine the dynamical basis of the varying nature of these contemporaneous teleconnections.

5. EOF analysis

In this section, we perform an empirical orthogonal function (EOF) analysis using the zonal and meridional components of the seasonal mean vertical shear vector. The analysis uses JASO mean data over the global tropical sector (30°S–30°N). The data are detrended and converted to anomaly fields prior to the analysis and the resulting EOFs are not rotated. The discussion in this section is restricted to only the leading two EOFs and their structure within the Atlantic.

The spatial patterns of the first and second EOFs are shown in Fig. 14. Together, these EOFs account for 44% of the total variance of the vertical shear within the global Tropics. The first EOF (Fig. 14a) has a nearly zonal structure, with the highest amplitude along the equator over central and eastern Atlantic. This EOF is clearly separated from the other EOFs and is associated with 36% of the total variance of global tropical shear. Within the MDR, the amplitude of the first EOF is much higher over the western portion compared to the central and eastern parts. This EOF bears a close resemblance to the pattern obtained by regressing the Niño-3 index onto the vertical shear (Fig. 11a).

The second EOF, shown in Fig. 14b, accounts for 8% of the total variance of vertical shear within the global Tropics. Compared to the first EOF, the signal in the second EOF is more prominent within the MDR. Thus, although this EOF accounts for only 8% of the variance of the shear over the entire tropical sector, the local variance explained within the MDR is expected to be much higher. A comparison of Figs. 11 and 14b reveals that this EOF is relatively closer to the pattern obtained by the regressing the vertical shear against the Sahel index than the Niño-3 index.

The temporal variation of the two EOFs is illustrated by their expansion coefficients shown in Fig. 15. The time series associated with the first EOF (Fig. 15a) exhibits an interannual variability with some evidence of modulation by a slower time scale variability. We note prominent peaks that correspond to past El Niño (e.g., 1972, 1982, and 1997) and La Niña (e.g., 1988, 1995, and 1999) events. An additional feature seen in Fig. 15a is that the amplitude of the expansion coefficient of the first EOF appears to be greater in its negative phase during the recent years and suggests a multidecadal modulation of the interannual variability.

The variability of the second EOF, as seen in its expansion coefficient (Fig. 15b), shows a dramatic difference from the previous EOF. A clear multidecadal variability is evident in this case. This is particularly striking in the 5-yr running mean of the expansion coefficients (solid line in Fig. 15b). We note that the phase of this EOF switches from negative (weak shear) to positive (strong shear) around 1970 and reverts to negative during the early 1990s. From Fig. 15b, it may be inferred that this mode has a time scale on the order of 40 yr. Since the signal associated with second EOF is strongest within the MDR (Fig. 14b), this suggests that the anomalous shear associated with it will have a modulating effect on the frequency of tropical cyclogenesis on a multidecadal time scale. This is consistent with Goldenberg et al. (2001) who used a simple measure of the vertical shear within the south-central portion of the MDR and showed that its interannual variability is superimposed on a multidecadal signal. Furthermore, the present analysis, based on the EOFs, also yields the spatial structure of the vertical shear mode that varies on the multidecadal scale.

A quantitative measure of the associations between the leading two EOFs, eastern Pacific SST, Sahel precipitation, and MDR tropical cyclone activity can be obtained from the linear correlation coefficients listed in Table 1. The correlation between the first EOF and MDR shear is 0.39. The second EOF correlates with MDR shear at 0.49, and is thus associated with about 25% of the MDR shear variance. Thus the second EOF has strong local contribution within the MDR despite accounting for only 8% of the variability of the shear over the entire Tropics.

The correlations with the Niño-3 index show inter-
esting differences between the two EOFs. The first EOF shows the strongest association, consistent with the pattern of shear seen in Figs. 11a and 14a. The correlation for this case is 0.86 and indicates that almost 75% of the variance of the first EOF can be related to the eastern Pacific SSTs. The second EOF shows an anticorrelation (−0.11), although not significant at the 95% level. However, this does mark a departure from the positive correlation seen for the first EOF (Table 1) as well as for the total shear (Fig. 11a). This suggests that the mechanism that relates eastern Pacific SST to the tropical Atlantic shear on interannual time scales may not be active on a multidecadal time scale.

The correlations with the Sahel index show that both EOFs have an inverse relationship with West African precipitation. Consistent with Fig. 11b, this indicates that the MDR shear is reduced during anomalous wet conditions in the Sahel and is enhanced during anomalous dry conditions. Compared to the first EOF, the second EOF is relatively better correlated with the Sahel index. The relationship between the second EOF and Sahel rainfall, together with the multidecadal variability of this mode, is consistent with the observed multidecadal variability of Sahel rainfall (e.g., Ward 1998). Furthermore, the uniformity in the sign of the correlations for both EOFs suggests that the mechanism that connects Sahel rainfall and MDR shear is the same on both interannual and multidecadal time scales. Thus, in this context, it appears that the first EOF may be interpreted as an ENSO mode while the second EOF may be considered to be a non-ENSO, multidecadal mode.

The final set of correlations presented in Table 1 relates the EOFs to the MDR tropical cyclone activity.
Both EOFs are correlated with MDR tropical cyclone activity at almost the same level, and each explains about 16% of the variability of tropical cyclone activity. Another measure of the relationship between the second EOF and MDR tropical cyclone activity can be gained by considering the number of storms that occurred during the positive and negative phases of the multidecadal oscillation. A total of 80 storms formed within the MDR during 1970–92 while 131 storms formed in the remaining 23-yr period. This clearly shows that the weak shear phase of the second EOF was significantly more active, with almost twice the number of tropical cyclones than during the strong shear phase.

6. Summary and discussion
The results presented in the preceding sections confirm that seasonal mean vertical wind shear is a strong factor in determining seasonal tropical cyclone activity, explaining almost 50% of the variability of these storms within the central MDR. Composites of various fields for the extreme shear seasons show that the anomalous circulations extend beyond the MDR, and they exhibit both tropical and extratropical connections. The relationship between vertical shear and ENSO takes the form of a zonally oriented circulation that mainly impacts the western MDR. On the other hand, the circulation associated with the Sahel rainfall is most prominent within the central MDR with significant anomalies that extend northeastward across this region.

Running correlations using 21-yr segments indicate that the contemporaneous relationship between ENSO and MDR vertical shear have strengthened during the recent decades. A similar analysis performed with the Sahel rainfall indicates that its association with MDR shear as well as tropical cyclone activity has degraded during the same period. There is evidence in the literature that suggests that the atmospheric response to ENSO forcing has undergone changes on decadal time scales. Kumar et al. (1999) showed that the contemporaneous association between ENSO and the Indian monsoon has weakened after the late 1970s and suggested that this is related to a southeastward shift in the Walker circulation during the recent decades. Janicot et al. (2001) found that the summer ENSO–Sahel rainfall teleconnection has become stronger after the mid-1970s. The variability in the strength and nature of these teleconnections are most likely due to the changes in the large-scale background circulation forced by slowly varying SSTs (e.g., Janicot et al. 2001; Kinter et al. 2002). The variable nature of the relationship between MDR shear and the Sahel places the strong correlations reported by past studies (Landsea and Gray 1992; GS96) within the context of decadal-scale variability. However, further work is needed to establish the physical mechanism that underlies this change.

Dominant spatial patterns of shear are extracted using the method of eigenvector decomposition applied to the data within the tropical sector. The structures most relevant to the shear within the MDR are captured by the first and second EOFs. The close relationship between the leading EOF and eastern Pacific SST suggests that this pattern be viewed as an ENSO mode.
The second EOF has a higher amplitude within the central MDR and varies on a multidecadal time scale. This EOF resembles the pattern obtained by regressing the Sahel rainfall index on the total vertical shear. The phase of this EOF switches from negative to positive around 1970 and remains in that mode until the early 1990s. This implies that the shear anomaly associated with this EOF is less conducive to tropical cyclone formation during the 1970s and 1980s as compared to the preceding and following decades. The present study concurs with a similar result reported by Goldenberg et al. (2001) and provides additional information by describing the spatial pattern of the shear that exhibits this multidecadal variability.

The present study has not explicitly addressed the physical mechanisms that link MDR vertical shear to remote SST and rainfall forcing on interannual and multidecadal time scales. The former was considered by GS96 who concluded that the mechanism involved near-equatorial zonal anomalies such as those associated with the Walker circulation seen in time mean fields. However, the multidecadal variability needs further examination. In the previous section we found that the second EOF is significantly correlated with Sahel precipitation and varies on multidecadal scales. The driving mechanism for this low-frequency variability is expected to involve non-ENSO oceanic forcing. As noted by Goldenberg et al. (2001), the likely source is the multidecadal mode of variability of Atlantic SST seen in previous studies (e.g., Mestas-Nuñez and Enfield 1999). Indeed, when the expansion coefficient of the second EOF is correlated with global SSTs, the strongest association appears within the Atlantic (not shown). The physical connection between the Atlantic multidecadal mode and MDR vertical shear may occur directly via the local SST forcing and also indirectly by modulating Sahel precipitation. Additional analysis, using observational data as well as numerical models are required to better understand the underlying processes.

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