Interannual-to-Multidecadal Variability of Vertical Shear and Tropical Cyclone Activity

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ABSTRACT

Spatiotemporal patterns of tropics-wide vertical shear variability are extracted after separating a 58-yr data record into high-frequency (HF, periods of 1.5–8 yr) and low-frequency (LF, periods greater than 8 yr) components. The HF vertical shear variability is dominated by circulation anomalies associated with the El Niño–Southern Oscillation (ENSO). The LF variability is primarily contained in two multidecadal patterns and a near-decadal pattern.

The multidecadal modes are strongest within the tropical Atlantic and are correlated with Sahel precipitation and interhemispheric sea surface temperature (SST) anomalies. The results suggest that the multidecadal variability of vertical shear over the Atlantic is linked to atmospheric circulation anomalies forced by the variability in Sahel precipitation. The decadal mode is strongest within the central Pacific and is correlated with Pacific decadal oscillation (PDO)-like SST anomalies. The circulation associated with this anomalous shear pattern appears to be consistent with the atmospheric response to the PDO-related diabatic heating anomaly over the central Pacific.

The relationship between vertical shear and seasonal tropical cyclone activity, as defined by the accumulated cyclone energy (ACE), is examined for the Atlantic, eastern Pacific, and western Pacific Oceans. The results show that global modes of vertical shear and seasonal average ACE are not consistently related in all three regions. It is only in the Atlantic Ocean that seasonal ACE is most consistently limited by vertical shear. This calls into question the utility of vertical shear as an independent predictor of seasonal tropical cyclone activity, particularly over the western Pacific Ocean.

1. Introduction

Tropical cyclone (TC) records from various ocean basins indicate interannual-to-decadal changes in their genesis frequency (e.g., Shapiro 1982; Gray 1984; Chan and Shi 1996; Elsner et al. 1999; Chia and Ropelewski 2002). This variability of TC activity is driven in part by the variability of environmental factors that include sea surface temperature (SST) and vertical wind shear. It is widely recognized that vertical wind shear exerts a strong control over the genesis of individual TCs (e.g., Gray 1968). Measures of basinwide vertical shear are invariably included as predictors of seasonal TC activity in various statistical and dynamical forecasts schemes (e.g., Gray et al. 1993; Lehmiller et al. 1997; DeMaria et al. 2001; Chu et al. 2007). Given that there are interannual and decadal fluctuations in TC activity, it is of interest to examine the corresponding changes in large-scale vertical shear and to establish whether there is a systematic relationship between the two on various time scales. In this study, we document the variability of tropics-wide vertical shear on interannual, interdecadal, and multidecadal time scales, and we examine the relationship with TC variability within the North Atlantic and North Pacific basins.

a. Background

Climate variability on the interannual time scale is predominantly driven by circulation changes accompanying El Niño–Southern Oscillation (ENSO). The impact of
ENSO on tropical cyclones has been a focus of numerous past studies. In the Atlantic, tropical cyclone activity is suppressed during El Niño periods and enhanced during La Niña (e.g., Gray 1984) periods. In the central North Pacific, more TCs form, on average, during El Niño years than during non–El Niño years (Chu and Wang 1997; Clark and Chu 2002). In the western North Pacific, during El Niño years, TCs form south and east of the climatological genesis region (e.g., Pan 1982; Chan 1985; Chia and Ropelewski 2002) and are more intense and long lived (e.g., Camargo and Sobel 2005). ENSO-related fluctuations in TC activity over the Atlantic have been linked, in part, to the associated changes in the magnitude of vertical shear (e.g., Goldenberg and Shapiro 1996). The role of vertical shear in the interannual shift in TC genesis location in the western North Pacific is less clear, although Chia and Ropelewski (2002) found that the mean genesis location of TCs corresponds to reduced shear as compared to climatology. The contribution of ENSO-related vertical shear in modulating TC activity over the central and eastern North Pacific also needs further scrutiny.

The frequency of tropical cyclogenesis also varies on interdecadal time scales. In the North Atlantic, Elsner et al. (1999) found a near-decadal oscillation in TC occurrence. In the central Pacific, Chu and Clark (1999) noted that the number of TCs during the period 1966–81 was significantly lower compared to 1982–96. Chu (2002) found that the latter epoch was associated with a favorable large-scale environment, including lower vertical shear over the central Pacific. An important source of interdecadal climate variability is the Pacific decadal oscillation (PDO), which has an ENSO-like spatial signature in the SST field (e.g., Trenberth and Hurrell 1994; Latif and Barnett 1996; Zhang et al. 1997; Mantua et al. 1997). The PDO SST structure consists of a tongue of same-signed SST anomalies stretching from the equatorial central Pacific to the eastern North Pacific, extending along the West Coast of the United States, and up to the subpolar North Pacific. An opposite-signed SST anomaly is found in the subtropical latitudes of the central North Pacific. Chu and Clark (1999) suggested that the decadal variability of TCs over the central Pacific is linked to the PDO. However, a close examination of the relationship of the PDO, basinwide vertical shear, and TC activity over the Atlantic and Pacific has yet to be performed.

In addition to interannual and interdecadal changes, multidecadal fluctuations in TC frequency in the Atlantic and Pacific have also been documented. In the Atlantic, TCs were more frequent between 1940 and 1960, and they have been since 1995 compared to 1970–90 (Landsea et al. 1999; Elsner et al. 2000). Goldenberg et al. (2001) have suggested that the recent upsurge in TC activity in the Atlantic is a part of this multidecadal fluctuation and have linked it to the Atlantic multidecadal oscillation (AMO). The AMO is generally used to describe the multidecadal warming and cooling of the North Atlantic surface (e.g., Folland et al. 1986; Kushnir 1994; Schlesinger and Ramankutty 1994; Delworth and Mann 2000), with the largest SST anomalies in the tropical North Atlantic and in the region south of Greenland (e.g., Mestas-Núñez and Enfield 1999). Vimont and Kossin (2007) suggest that the AMO’s impact on Atlantic hurricane activity is mediated through the Atlantic meridional mode (AMM), a dynamical mode of the tropical ocean–atmosphere system (e.g., Servain et al. 1999; Xie and Carton 2004). The SST signal associated with the AMO is not confined to the Atlantic and exhibits an interhemispheric gradient. Climate model simulations (e.g., Delworth and Mann 2000; Knight et al. 2005) have indicated that this multidecadal SST fluctuation is related to intrinsic variability in the oceanic thermohaline circulation (THC). Conversely, Andronova and Schlesinger (2000) and Mann and Emanuel (2006) have suggested that the Atlantic SST anomalies in recent decades have been dominated by warming and cooling by anthropogenic factors and not by intrinsic natural climate variability attributed to the AMO. Wang and Lee (2008) have reported an increasing shear trend within the Atlantic main development region (MDR) over the period 1949–2006 and have suggested a link to a warming climate. A similar increase in vertical shear within the western Atlantic in a multimodel suite of future climate projections was also found by Vecchi and Soden (2007).

The atmospheric circulation anomalies associated with the AMO impact the tropical Atlantic and the Pacific as well as higher latitudes in the Atlantic sector (e.g., McCabe et al. 2004; Sutton and Hodson 2007). Goldenberg et al. (2001) found that the vertical shear and cyclogenesis frequency within the Atlantic MDR also exhibit multidecadal fluctuations and suggested a link with AMO SST variability. Chelliah and Bell (2004) identified a multidecadal mode of tropical climate variability that is related to tropical surface temperatures and precipitation anomalies and is consistent with the AMO.

Bell and Chelliah (2006) examined the leading tropical modes associated with the interannual and multidecadal variability of North Atlantic hurricanes. The two leading multidecadal modes of tropical variability identified in their study were found to correlate strongly with multidecadal Atlantic TC activity as defined by the accumulated cyclone energy (ACE) index (Bell et al. 2000). They also found that these modes were associated with anomalous zonal wind shears over the Atlantic, which they suggested could significantly impact TC activity. In their climatology of Atlantic vertical shear, Aiyyer and Thorncroft (2006) found a pattern of vertical
shear that varies on multidecadal time scale and is correlated with Sahel precipitation anomalies.

b. Objectives

In light of the growing interest in understanding the physical basis for the control of TC activity by slowly evolving oceanic modes such as the PDO and the AMO, it is important to examine, in depth, the variability of vertical shear on their respective time scales. The spatiotemporal variability of TC activity also needs to be systematically compared to corresponding shear variability. Furthermore, because previous studies have focused on individual basins, and in particular the Atlantic, it is of interest to study the tropics-wide distribution of vertical shear to find patterns that are common to the entire tropics. Motivated by these considerations, the aim of this study is to take a unifying, large-scale approach that directly focuses on vertical shear variability and its relationship with TC genesis frequency.

We separate the high-frequency (HF) and low-frequency (LF) components of tropics-wide vertical shear and extract their spatiotemporal patterns and relationship with upper- and lower-level atmospheric circulations. To identify possible forcing mechanisms in the form of persistent diabatic heat sources, we also examine their links with global SST and precipitation anomalies on their respective time scales. The relationship between vertical shear and tropical cyclones on these time scales is also examined. This study does not examine secular trends in the vertical shear. As such, all data are detrended prior to analysis.

2. Data and method

Gridded monthly-mean zonal and meridional wind fields at the 850- and 200-hPa levels are obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al. 1996) reanalyses. The wind data are on a 2.5° latitude–longitude grid. The SST fields are obtained from the Met Office Hadley Centre Sea Ice and Sea Surface Temperature version 1 (HadISST1; Rayner et al. 2003) and are available on a 1° latitude–longitude grid. The tropical cyclone tracks and intensity are derived from the best-track datasets available from the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC).

Following Enfield and Mestas-Núñez (1999), we separate the wind data into HF and LF components. The HF part of the data is derived by applying a 1.5–8-yr bandpass filter on the monthly fields, while the LF part is created using a low-pass filter that retains all periodicities greater than 8 yr. The July–October (JASO) monthly fields are averaged to get seasonal fields. The seasonal mean vertical shear is defined as the vector difference between the JASO mean wind fields at 200 and 850 hPa. We choose the months JASO because they represent the most active period within a year for TC formation in the western Pacific, eastern Pacific, and the Atlantic, the three ocean basins of interest to the present study. A future study will examine the Indian Ocean, Bay of Bengal, and Arabian Sea regions. Figure 1 shows the JASO mean vertical shear in the tropics and the

![Fig. 1. Mean 200–850-hPa vertical wind shear magnitude (m s⁻¹, shaded) with (a) mean vector shear (arrows) and (b) Pacific and Atlantic TC genesis locations. Data for JASO season (1948–2004).](image-url)
distribution of TC genesis positions. It is evident that TCs form preferentially within regions of weak mean shear (Fig. 1b). Regional variations in the direction of the vertical shear vectors can be noted. The vertical shear is easterly over the western Pacific and westerly over the central Pacific and the Atlantic. The mean shear over the eastern Pacific is relatively weak.

To extract the dominant modes of vertical shear variability, empirical orthogonal function (EOF) analysis of the HF and LF vertical shear fields is performed. The analysis uses both the zonal and meridional components of vertical shear over the entire tropical strip that lies between 30°S and 30°N. Prior to obtaining the EOFs, the linear trend from the shear data is removed. Figure 2 shows the shear trend for the period 1948–2004. As noted by Wang and Lee (2008), the AT MDR is associated with an increasing shear trend. The increasing shear in the Atlantic also appears to be a common feature in future climate simulations and is a manifestation of more El Niño–like conditions and a weaker Walker circulation (Vecchi and Soden 2007). Conversely, the shear trend is not prominent over the cyclogenesis areas of the eastern and western Pacific.

3. Vertical shear modes

a. Interannual mode

The leading EOF of the HF component of vertical shear and the time series of its expansion coefficient are presented in Fig. 3. The vectors in Fig. 3a depict the vertical shear obtained by regressing the expansion coefficients on the zonal and meridional winds at 200 and 850 hPa. The shading shows the percent variance of the total (unfiltered) shear accounted by this mode. The shear signal associated with this mode is most prominent over the western and central Pacific, between 20°S and 10°N. The contribution of this mode to the total shear exceeds 50% within this region. Vertical shear anomalies can also be seen over the eastern Pacific and the Atlantic. Although this pattern covers much of the tropical eastern North Pacific, it impacts only the western portion of the Atlantic MDR. Thus, although this EOF accounts for 10%–30% of the total shear within the Caribbean, it does not contribute significantly to the total shear variability within the central and eastern MDR. The shear pattern associated with this EOF also extends from eastern North Africa into the Arabian Sea, where locally more than 50% of the total vertical shear variability resides in this EOF component.

The principal component (PC) time series of the leading HF EOF (Fig. 3b) clearly exhibits interannual fluctuations. The variability is closely tied to that of ENSO, as evident from the large positive and negative deviations corresponding to prominent El Niño (e.g., 1972, 1987, 1997) and La Niña (e.g., 1975, 1988) years, respectively. The anomalous shear associated with the positive phase of this mode is easterly over the central and western Pacific and westerly over the eastern Pacific and tropical Atlantic (Fig. 3a). A comparison with Fig. 1a shows that this leads to a stronger-than-normal shear over most of the Pacific and the Atlantic MDR. The converse is applicable to the negative phase of this mode.

The association between this EOF mode and ENSO is confirmed when unfiltered global SST and 200- and 850-hPa streamfunction fields are regressed onto the PC time series and the well-known patterns associated with ENSO are recovered (not shown). These results confirm that the leading EOF of the HF component of global shear is forced by ENSO. The structure of the ENSO-related vertical shear matches that found by Goldenberg and Shapiro (1996), who examined the tropical Atlantic sector. Although the SST and atmospheric circulation anomalies associated with ENSO have been well documented in the past, the present analysis has further highlighted the tropics-wide pattern of vertical shear that varies with this mode.

b. Decadal-scale modes

The EOF analysis of the LF component of vertical shear does not yield a single EOF mode that dominates the variability, as is in the case of the HF component of shear. Instead, there are three leading EOF modes (EOF1–EOF3), which are the subject of this section. The first and third EOFs exhibit multidecadal-scale variability, while the second EOF exhibits interdecadal-scale variability.
1) MULTIDECADAL MODES

Figure 4 shows the two multidecadal modes and the percent variance of the unfiltered shear associated with them. The vertical shear in LF EOF1 (Fig. 4a) is most prominent over the tropical eastern Atlantic. Locally, as much as 50% of variance in vertical shear is accounted for by this mode. However, this local maximum occurs between the equator and 10°N and lies south of the Atlantic MDR. The variance associated with this mode in the central portion of the Atlantic MDR is about 10%–30%. The tropical eastern Pacific is also associated with some signal in vertical shear. However, much of the shear lies to the south of the equator, with only a marginal coverage over the climatological genesis area in the eastern North Pacific (cf. Fig. 1b). The shear anomalies in this mode over the western and central Pacific are negligible.

The LF EOF3 (Fig. 4b), which represents the secondary multidecadal mode, includes a nearly zonal shear anomaly that extends across the Atlantic MDR. It also has significant anomalies over the equatorial central and eastern Pacific but not over the TC genesis region of the eastern Pacific. The amplitude over the western Pacific is very low.

The temporal evolution of these modes, depicted by the principal component time series (Fig. 5), exhibits slow oscillations with a time scale of multiple decades. These modes were out of phase till around 1975 and appear to vary nearly in phase since then. Both modes show a swing toward the positive phase during the mid-1990s, which coincides with the latest upsurge in Atlantic TC activity. During the relative lull between 1970 and 1990, the modes tended to be in negative phase (Fig. 5). As seen in Fig. 4, the positive phase of these modes represents anomalous easterly shear within the tropical Atlantic. A comparison with Fig. 1a shows that the positive phase of these modes leads to a weaker-than-normal shear over the Atlantic. Conversely, the sense of the shear anomalies is opposite over the eastern Pacific. Whereas EOF1 is associated with westerly shear, EOF3 is associated with easterly shear. Of these two, only EOF3 has any appreciable signal over the central and western Pacific.

Figure 6 shows the SST fields that are associated with the two multidecadal modes. They were obtained by
regressing unfiltered global SST fields on the respective principal component time series. In both cases, positive anomalies can be seen over tropical and extratropical regions of North Atlantic and North Pacific. Negative anomalies are found in the southern Indian Ocean and locally in the extratropical southern Atlantic. The SST anomaly pattern associated with LF EOF1 (Fig. 6a) matches the leading rotated EOF of non-ENSO SST in Mestas-Núñez and Enfield (1999). The overall spatial and temporal structure of this mode is consistent with the description of the SST pattern attributed to the AMO (e.g., Kawamura 1994; Kushnir 1994; Mestas-Núñez and Enfield 1999; Delworth and Mann 2000). The anomalous SST patterns in Fig. 6 are broadly consistent with those associated with the leading tropical multidecadal modes described by Bell and Chelliah (2006).

The two multidecadal modes are also regressed against global precipitation fields taken from the global historical climatology network (GHCN). The results (not shown) exhibit distinct regional variations. In both cases, the positive phase is associated with anomalously wet conditions over the Sahel and dry conditions over South America. However, the precipitation anomalies corresponding to the leading multidecadal mode (LF EOF1) are stronger over these areas. The reduced precipitation over the Sahel between 1961 and 1993 has been extensively documented (e.g., Folland et al. 1986; Ward 1998). A concurrent increase in rainfall over the Amazon for the same period has also been reported in
the past (e.g., Chu et al. 1994; Chen et al. 2001). The two multidecadal modes were mostly in their negative phase during this period, with the exception of the first few years when EOF1 was positive. As noted in Bell and Chelliah (2006), these multidecadal modes appear to be related to the seesaw in decadal-scale precipitation anomalies over the Sahel and South America. Although the specifics of the physical mechanisms underlying the multidecadal precipitation fluctuations in these two regions are still being investigated, there is sufficient evidence in the literature that points to oceanic forcing on this time scale (e.g., Folland et al. 1986). The AMO is regarded as being central to this variability.

The regressed circulation anomalies (Figs. 7) highlight how the vertical shear patterns seen in Fig. 4 arise. For LF EOF1, the prominent feature at the upper level consists of anticyclonic gyres straddling the equator over the Atlantic (Fig. 7a). The corresponding velocity potential field (not shown) contains upper-level divergence located over central Africa and convergence over South America. Consistent with Chelliah and Bell (2004), a comparison with the precipitation anomalies (not shown) suggests that these features are a part of the stationary response to the diabatic thermal forcing (e.g., Gill 1980) associated with Sahel and eastern Atlantic ITCZ precipitation anomalies. A relatively weaker stationary circulation response is also seen over the eastern Pacific. In this case, the positive phase of the multidecadal shear mode is associated with a pair of cyclonic gyres (Fig. 7a) on either side of the equator. This is consistent with the expected response to the negative precipitation anomalies over Central and South America. The upper-level circulation anomalies for LF EOF3 (Fig. 7b) appear to be relatively more zonal in the tropics, particularly over the Atlantic sector, where the classic stationary response to Sahel precipitation forcing is weaker compared to LF EOF1. This is likely due to relatively weaker precipitation anomalies corresponding to this mode.

These results suggest that the cool phase of the AMO is associated with westerly vertical wind shear over the tropical Atlantic, which augments the climatological wind shear in this region. The connection between anomalous SST and wind shear appears to be made through atmospheric circulations induced by anomalous precipitation over the Sahel and the eastern Atlantic. The atmospheric circulation patterns associated with these modes is consistent with the leading tropical multidecadal modes of Bell and Chelliah (2006). These results are also consistent with earlier studies (Gray 1990; Landsea and Gray 1992; Goldenberg and Shapiro 1996) that showed a link between Atlantic tropical cyclones and Sahel rainfall.
The second EOF mode extracted from the LF vertical shear data is shown in Fig. 8. The vertical shear signal in this mode is significant only within the central and western Pacific. Locally, this pattern contributes approximately 10%–30% of the variability of the total seasonal-averaged shear. The temporal variation of this mode (Fig. 8b) shows a period that ranges between 10 and 15 years. It can be seen that the positive phase of this mode is associated with easterly vertical shear within the western and central Pacific. Since the mean shear is easterly within the western North Pacific, this shear mode enhances the mean shear in this region. The amplitude of the vertical shear within the eastern Pacific and the Atlantic is negligible.

The regressed SST field (Fig. 9a) shows an ENSO-like signal in the central Pacific. The positive phase of this mode is associated with warm SST anomalies in the tropical central and eastern Pacific as well as along the west coast of North America. Opposite-signed anomalies are present in the midlatitudes over the central North and South Pacific. The regressed SST pattern bears a strong resemblance to the PDO SST mode seen in the global SST fields of the analysis (e.g., Zhang et al. 1997; Enfield and Mestas-Núñez 1999). However, the time series of the expansion coefficient of this shear mode (Fig. 8b) does not exactly match the temporal variability of the PDO in Enfield and Mestas-Núñez (1999). Nevertheless, the tendency of this mode to be in its warm phase during the 1980s and 1990s and cool phase during the 1970s is in general agreement with past analyses of the PDO.

The regressed precipitation from the GHCN dataset (not shown) consists of negative anomalies over South America and along a zone stretching from the Guinea coast to Ethiopia. In the NCAR–NCEP precipitation data (not shown), positive precipitation anomalies are found over the equatorial central western Pacific, consistent with the spatial structure of the regressed SST anomalies (Fig. 9a).

The 200-hPa circulation fields associated with this mode (Fig. 9b) contain a nearly symmetric pair of
zonally elongated anticyclonic gyres over the equatorial central Pacific. This stationary response to the diabatic forcing associated with convection over the warm SST anomalies in Fig. 9a is consistent with previous studies (e.g., Higgins et al. 2000). The streamfunction anomalies are nearly identical to the ENSO-related circulation, except that in this case, the high amplitude values do not extend across the entire tropics.

These results show that the decadal mode of vertical shear variability is related to the PDO and has the greatest influence over the central and western Pacific. The vertical shear field is an outcome of the atmospheric circulation response to precipitation anomalies in the tropical Pacific that are tied to the PDO.

4. Relationship with TC activity

In the present section, TC activity is examined in relation to the interannual, decadal, and multidecadal shear modes. A succinct measure of the overall strength of TC activity is given by the ACE index (Bell et al. 2000). However, it should be noted that the ACE, by virtue of its definition, emphasizes the intensity more than genesis frequency. Figure 10 shows unfiltered normalized ACE and vertical shear time series for the three ocean basins covering areas associated with TC activity: Atlantic (10°–25°N, 270°–310°W); eastern Pacific (10°–25°N, 220°–250°W), and western Pacific (10°–25°N, 120°–160°E). These time series are for the unfiltered data. It is evident that, for the most part, ACE and shear are anticorrelated over the Atlantic and eastern Pacific. The coefficient of linear correlation ($R$) for the two time series is $-0.58$ for the Atlantic and $-0.49$ for the eastern Pacific. These correlations were found to be significant at the 0.05 level using the standard $t$ test. Conversely, the two time series are uncorrelated ($R = -0.06$) over the western Pacific.

The spatial patterns of the relationship between ACE and shear are examined by constructing ACE index maps. The instantaneous kinetic energy (KE)—defined as $\frac{1}{2}V_m^2$ for each TC, where $V_m$ is the maximum sustained wind speed at each time—is assigned to the nearest point on a grid with 5° latitude–longitude spacing. The 4-times-daily TC locations for tropical storm and higher-intensity categories from the best-track datasets for the Atlantic, eastern Pacific, and western
Pacific basins are used. The JASO seasonal total ACE map for each year is constructed by adding all 6-hourly ACE fields. The seasonal ACE and shear fields, with the long-term mean removed, are averaged for the top five positive and negative years, respectively, for each EOF. Thus, the resulting anomaly composite ACE and shear fields correspond to the extreme phases of the EOFs.

Figure 11 shows the difference between ACE (shaded) and shear (contours) composites for extreme years corresponding to each EOF. By comparing the magnitude and differences, the locations where shear limits ACE can be identified. For the interannual mode, the greatest negative difference in ACE and positive difference in shear are located over the western tropical Atlantic (Fig. 11a). There is some overlap of opposite-signed ACE and shear anomalies in both the eastern and western Pacific. However, in the latter, the relative magnitudes of ACE and shear anomalies are not comparable; that is, the ACE anomaly is large in areas of small shear anomalies. This indicates that shear may not be an effective limiting factor for ACE in this area. The multidecadal modes (LF01, LF03) also have a similar pattern of ACE and shear anomalies, with the Atlantic showing the most consistent opposing relationship. The weakest relationship is again seen over the western Pacific. Here, ACE and shear have the same-signed anomalies in LF01 (Fig. 11b), whereas shear anomalies are weak where ACE anomalies are strong in LF03 (Fig. 11d).

The decadal mode (LF02) does not have an appreciable signal in ACE or shear anomalies over the Atlantic (Fig. 11c). There is some overlap in the anomalies in the eastern Pacific, but the shear anomaly is weak over the region of the strongest negative ACE anomaly. Over the western Pacific, the shear anomalies are weakly negative where the ACE anomalies are relatively strongly positive.

These results suggest that a consistent relationship between ACE and vertical shear—one that indicates that ACE is limited by shear—is seen mainly over the Atlantic. This is evident in both the correlations in the unfiltered ACE and shear time series as well as the spatial
patterns of their anomalies. The relationship over the western Pacific appears to be the least consistent. Here, the ACE is either not limited by shear or appears to vary in concert with it.

5. Discussion

This study takes a tropics-wide view of vertical shear and extracts the spatiotemporal patterns of shear that vary on interannual and decadal time scales using 57 yr of data from the NCEP–NCAR reanalysis. These patterns are related to tropical forcing in the form of persistent precipitation anomalies on those respective time scales. The results show that the interannual variability of tropics-wide vertical shear is primarily a response to ENSO forcing. The decadal-scale variability shows two prominent patterns—one related to the AMO and the other to the PDO. The atmospheric circulation patterns that are related to the interannual- and decadal-scale vertical shear EOFs are also examined. Consistent with previous studies (e.g., Bell and Chelliah 2006), these atmospheric circulations appear to be forced by persistent diabatic heating anomalies induced by precipitation anomalies related to the ENSO, AMO, and PDO.

The impact of the ENSO-related vertical shear variability is strongest within the western Pacific, but it extends into the eastern Pacific and the Atlantic as well. The 200- and 850-hPa circulation patterns associated with this mode strongly resemble the idealized Gill solution to a tropical heat source.

The AMO-related vertical shear is primarily confined to the Atlantic and the eastern Pacific. In this case, the upper- and lower-level atmospheric circulations appear to be a response to Sahel precipitation anomalies varying on multidecadal time scales. Several studies have documented the multidecadal changes in Sahel precipitation [see Dai et al. (2004) for a review]. A major component of this variability includes a switch to drought conditions during the early 1970s and a recent swing toward increasing precipitation over the Sahel. These shifts appear to be coincident with changes in the basinwide shear in the Atlantic (Fig. 4b) and lend further support to the suggestion that the multidecadal change in Atlantic vertical shear is linked to Sahel precipitation forcing. In addition to the impact on vertical shear locally, the circulation patterns also extend northeastward into Europe and southeastward into South Africa.

The impact of the PDO on vertical shear is most prominent over the central and western Pacific. The 200- and 850-hPa circulation patterns indicate a close connection to the PDO-related precipitation anomalies over the equatorial central Pacific. The structure of the response is baroclinic locally and barotropic in the extratropics, as in the previous cases.

The global modes of vertical shear described above are further examined with regard to their relationship with TC activity over the western Pacific, eastern Pacific, and Atlantic. The results suggest that a consistent relationship, wherein enhanced vertical shear suppresses seasonal TC activity, as measured by the ACE index, is found only over the Atlantic. In particular, the relationship is most coherent in this basin for the leading interannual and multidecadal modes of shear. TC activity in the Atlantic MDR is suppressed during strong El Niño
years, and during decades when the Atlantic SSTs are cooler and Sahel rainfall is deficient. The vertical shear is stronger than normal under these conditions.

In contrast, the results show that the relationship between global shear modes and TC activity in the western Pacific is not coherent. This indicates that vertical shear variability does not strongly control TC activity in this basin. The results for the eastern Pacific region show a mixed response, with the most coherent relationship seen for the leading HF shear mode. This indicates that in these two basins, factors such as SST are more relevant to tropical cyclogenesis. The presence of a strong relationship between vertical shear and TC activity only within the Atlantic also raises the possibility that basinwide shear may not be a universally important factor in determining seasonal TC activity and that the covarying relationship in this basin is incidental—this possibility requires additional investigation. Furthermore, because of the much higher TC activity over the eastern and western Pacific, the seasonal mean shear may be modulated by TC circulation. Thereby, mean shear in these basins may not be an independent predictor of ACE.

Since shear and ACE are consistently related in the Atlantic on interannual and decadal time scales, it is also important to consider secular shear trends in projections of TC activity in future climates. Recent studies have suggested that the occurrence of more ENSO-like conditions in the Pacific, accompanied by a weakening of
the Walker circulation, will likely continue into a future warmer climate (Held and Soden 2006). As a result, vertical shear in the Atlantic is expected to increase. Vecchi and Soden (2007) found that a suite of multimodel simulations for the twenty-first century near-unanimously exhibit positive shear trends within the western portion of the Atlantic MDR. Conversely, their results also show that there is considerable uncertainty in future shear trends within the central MDR, where roughly half of the models show increases. Since the decadal shear mode (LF01), which is associated with Sahel rainfall anomalies, has the highest amplitude in this region, it is possible that the uncertainty in climate model projections of Sahel rainfall (e.g., Biasutti et al. 2008) may contribute to this model-to-model difference in shear trends. Thus, any inference drawn with regard to the influence of shear on future TC activity should also take into account the representation of the physical mechanisms associated with shear variability and trend in model simulations.

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