LOCAL MINIMUM OF TROPICAL CYCLOGENESIS IN THE EASTERN CARIBBEAN

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The eastern Caribbean is climatologically unfavorable for tropical cyclone development because of a complex of factors involving divergent, low-level winds that vary seasonally and may be affected by remote climate variables.

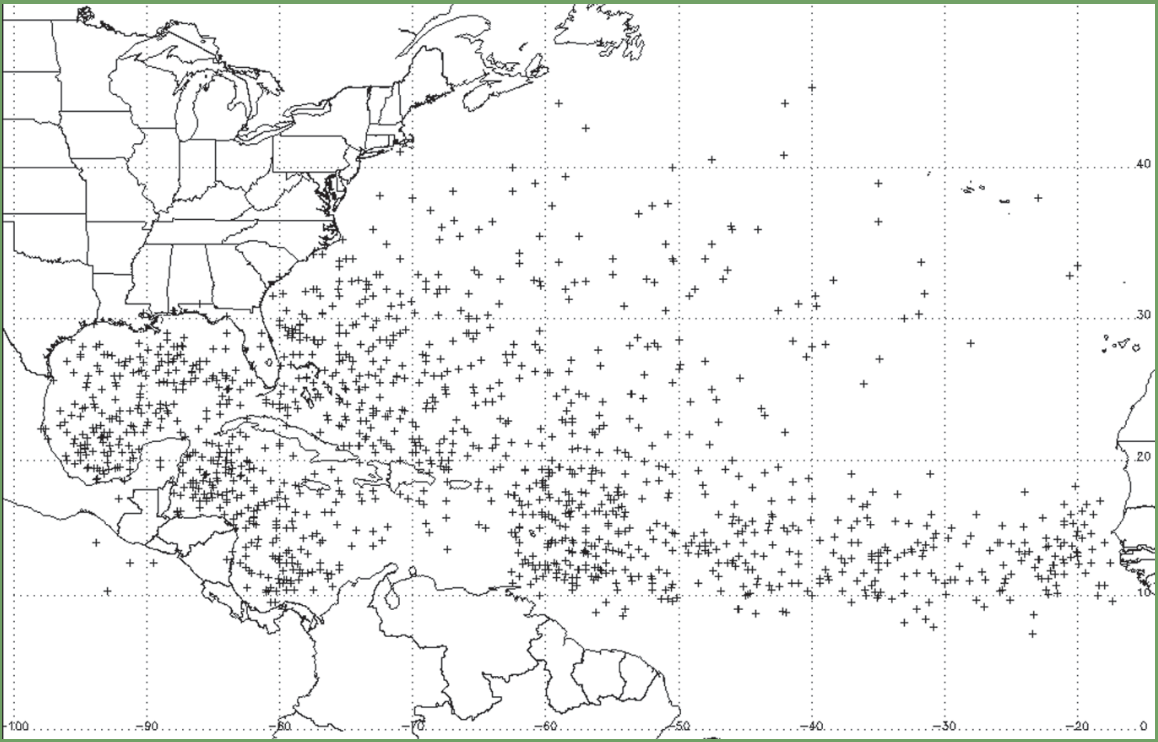

FIG. 1. Points of origin of all named tropical cyclones, Jun–Nov 1851–2008.

Hurricane forecasters have long been puzzled (e.g., Henry 1924) by the apparent tendency of nascent tropical cyclones to cease development or weaken as they traverse the eastern Caribbean Sea. Given the low latitude of this region, most of these tropical disturbances are those that develop from African easterly waves that are embedded in the deep, tropical easterlies over the North Atlantic Ocean. Oftentimes, these surface atmospheric waves or weak tropical cyclones and their associated convection unexpectedly decrease in intensity over the eastern Caribbean, only to redevelop once they enter the western Caribbean, posing a dilemma for forecasters. A map (Fig. 1) of the points of origin of all named tropical cyclones from June through November 1851–2008 reveals a distinct minimum of origin points from 10° to 20°N and from 75° to 60°W (the eastern Caribbean Sea) relative to locations east and west of this region within the same latitude band. Plots of more recent periods including the era of satellite observations and the Dvorak technique are qualitatively similar (not shown).

An example of a tropical disturbance that weakened upon entering the eastern Caribbean can be seen in Figs. 2a–c. Figure 2a shows the disturbance at 0015 UTC 16 July 2004 with healthy convection just west of the Lesser Antilles. However, only 3 h later (Fig. 2b), the convection collapsed, with no regeneration until around 1215 UTC (Fig. 2c). Figure 2d, constructed from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) 40-yr reanalysis project data (Kalnay et al. 1996), shows an area of preexisting mass divergence at 925 hPa ahead of the disturbance, whereas Fig. 2e illustrates subsidence at 700 hPa over this region. Satellite analyses before this period (not shown) show that other factors may be involved as well, such as orographic enhancement of convection by the islands, because convection was weaker as the disturbance approached the islands from the east. However, convection increased again by the time it reached 67°W longitude, as shown in Fig. 2c. Diurnal modulation of convection is also possible, but the regularity and semistationary nature of the preexisting mass divergence in the eastern Caribbean suggests that it may play a role in suppressing convection and is worthy of further investigation.

For years, the National Hurricane Center has colloquially referred to the eastern Caribbean region as a hurricane graveyard. A good example of this reference was in the forecast discussion for Tropical Depression Joyce in 2000:

> The outflow has improved and I would dare to say that it is favorable for strengthening. However . . . Tropical Depression Joyce is about to move into the area which the old timers call the hurricane graveyard. Historically . . . with a few exceptions . . . tropical cyclones do not develop in this area . . . Joyce is kept at 30 knots through 48 hours. Thereafter . . . some strengthening is indicated when the depression reaches the western Caribbean . . . if it survives . . . (Avila 2000).

In fact, Joyce dissipated following this discussion.

It is clear that an element of uncertainty surrounds the eastern Caribbean Sea with respect to forecasting the intensity and subsequent development of tropical disturbances and weaker tropical cyclones. Because of this uncertainty, there have been many cases when forecasters have maintained the status quo of a disturbance traveling through the eastern Caribbean Sea—even if conditions appear favorable for development—only to forecast its reintensification once it leaves the region. This study examines the possible climatological factors that may be contributing to this local minimum of tropical cyclogenesis. Because the vast majority of tropical cyclones that develop or enter the eastern Caribbean region eventually affect surrounding islands or landmasses, including the United States, it is imperative that forecasters understand the factors that are contributing to the lower frequency of tropical cyclone formation over the eastern Caribbean.

CONDITIONS FOR TROPICAL CYCLONE FORMATION. The conditions supportive of tropical cyclogenesis are generally well understood. These conditions (Gray 1968; Hennon and Hobgood 2003) are 1) a persistent area of convection; 2) sufficient absolute (planetary plus relative) vorticity; 3) little to no vertical wind shear near the cyclone center; 4) sufficient moisture; 5) sufficiently warm ocean and deep mixed layer; and 6) a state of atmospheric conditional instability.

For the local minimum of tropical cyclogenesis to be a real phenomenon, there must be some climatologically persistent condition that locally contributes to tropical cyclolysis. It is apparent that conditions 1, 2, 4, and 5 are not of particular concern. The persistence of convection is itself the topic of study, because convection is often observed to weaken unexpectedly over the eastern Caribbean. For areas north of 5°N, planetary vorticity becomes a negligible concern (Hennon and Hobgood 2003). The eastern Caribbean is located entirely north of this latitude. Likewise, we can discount the possibility of insignificant moisture playing a role in the eastern Caribbean, because the region is embedded within the deep tropics with

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prevailing surface easterlies advecting moisture from a generally uniform moisture source—the tropical North Atlantic.

Occasionally, the Saharan air layer (SAL) is advected westward into the eastern Caribbean, bringing in drier air and increasing the temperature inversion at the base of the SAL, which may inhibit the development and intensification of tropical disturbances (Dunion and Velden 2004). However, it is important to emphasize that although the SAL can be detrimental to tropical convection, its associated inhibiting factors are advected from east to west across the tropical North Atlantic. Therefore, if the eastern Caribbean is affected by the dry air, the rest of the tropical North Atlantic to the east of the region should also be affected—perhaps to an even greater extent, assuming that the dry and warm SAL gradually moderates as it is advected westward. Thus, any negative effects of the SAL should not be unique to the eastern Caribbean and cannot explain the local minimum of tropical cyclogenesis in that region.

It can be seen in satellite data that the eastern Caribbean Sea does not exhibit significant departures in sea surface temperatures (SSTs) from the surrounding ocean. The only difference is that there is a lag in the onset of the annual warming when compared to the Gulf of Mexico and the western Caribbean (Wang and Enfield 2001). There is no significant

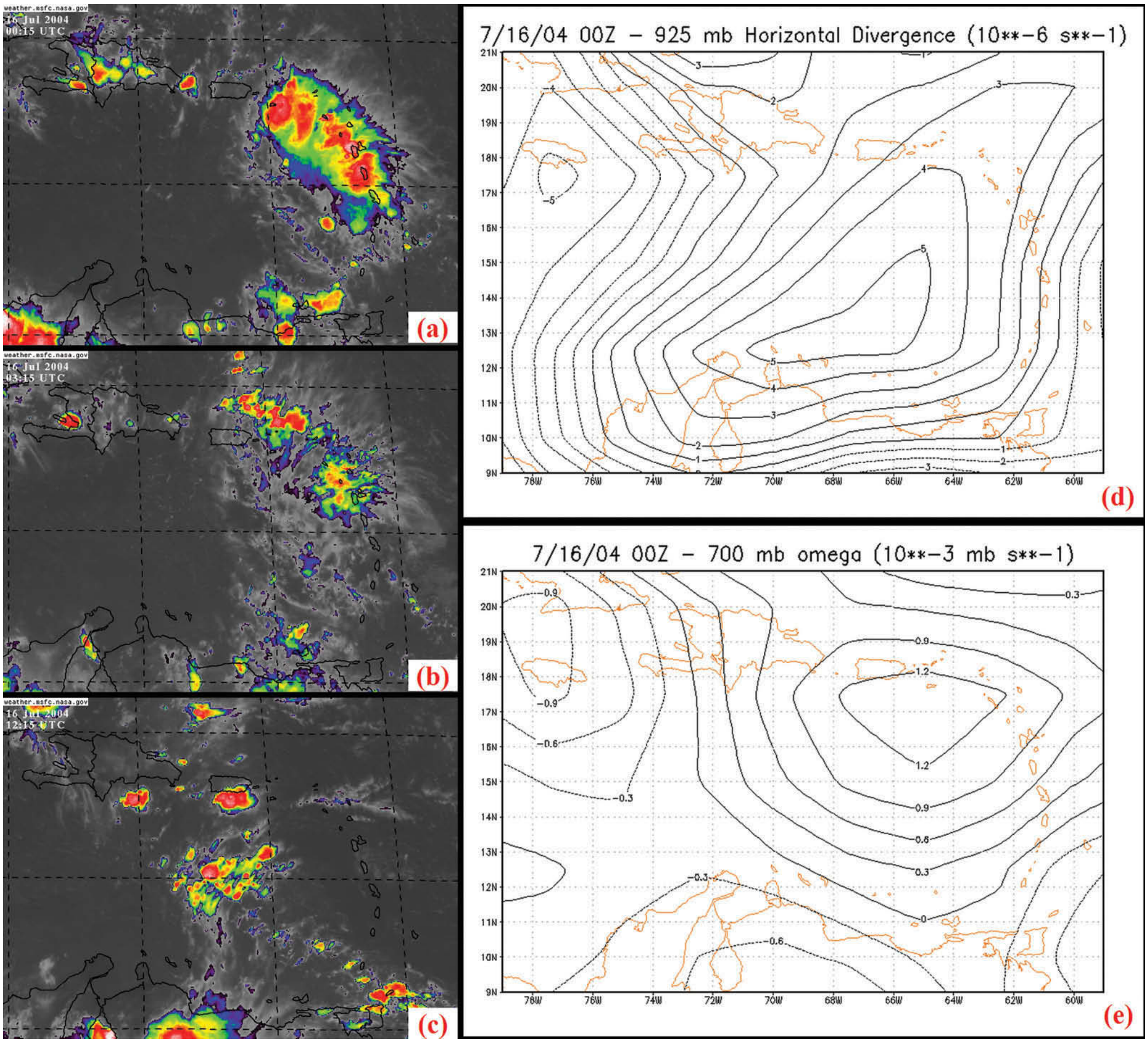

Fig. 2. (a) IR satellite image of a tropical disturbance, embedded within the tropical easterlies, just entering the eastern Caribbean at 0015 UTC 16 Jul 2004; (b) IR satellite image showing a substantial decrease in convection in the tropical disturbance only 3 h later; (c) IR satellite image indicating a regeneration of convection at 1215 UTC; (d) NCEP–NCAR reanalysis showing the area of preexisting divergence [10^{-6} s^{-1}] at 925 hPa at 0000 UTC 16 Jul 2004 that may have contributed to the weakening of the convection entering the eastern Caribbean; and (e) analyzed 700-hPa vertical motion (omega; [10^{-3} hPa s^{-1}]) at the same time as (d).

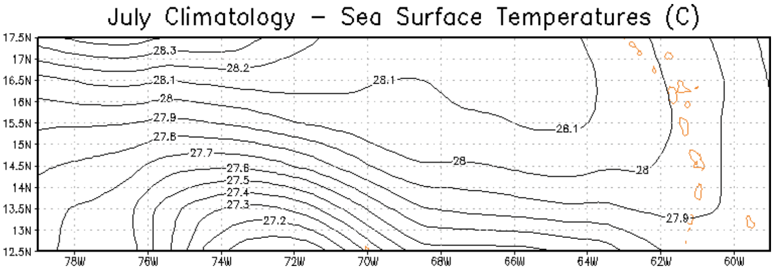

Fig. 3. Jul mean (1971–2000) SSTs (°C) from the NCEP–NCAR reanalysis.

“cold pool” associated with the eastern Caribbean that would explain the local minimum of tropical cyclogenesis in the region. There are indications of cooler SST because of upwelling by the easterlies in the southwestern Caribbean Sea (Inoue et al. 2002), but that is outside the geographic domain of this study. For example, climatological SSTs exceed 27°C throughout the eastern Caribbean Sea during July (Fig. 3), as well as during the other months, from June through November (not shown). Interestingly, the area-averaged, July mean SST in the 12.5°–17.5°N latitude band of Fig. 3 is the same (27.9°C) over the eastern Caribbean (75°–60°W) as it is just to the west (82.5°–75°W) of the region and actually warmer than it is (27.2°C) just to the east (60°–45°W). Notice how SSTs increase northward over the eastern Caribbean in Fig. 3. This is likely due to open-water upwelling south and downwelling north of the low-level easterly flow. The meridional extent of the relatively cool southern water may vary with time according to the action of oceanic eddies. Weakening of the atmospheric easterly flow later in the season would weaken the upwelling, creating a more favorable environment for tropical cyclogenesis.

To complete our discussion of favorable tropical cyclogenesis conditions, it is necessary to address the remaining two (conditions 3 and 6): little to no vertical wind shear near the cyclone center and a state of atmospheric conditional instability. If condition 3 were to be considered with a zonally averaged, lower-tropospheric wind field, then, in the context of the deep tropics, the vertical wind shear can be increased by increasing the magnitude of the upper-level westerlies. Although there is no evidence to suggest that the eastern Caribbean region is more likely than areas nearby at the same latitude to experience the temporal, synoptic-scale intrusions of upper-level westerlies from the midlatitudes, this region is a climatologically preferred location for the tropical upper-tropospheric trough (TUTT). This feature, in combination with the low-level easterlies, could enhance the vertical wind shear (Fitzpatrick et al. 1995; Goldenberg and Shapiro 1996). Last, although condition 6 includes thermodynamic mechanisms that cause vertical motion, it can be broadly inferred to include the presence of dynamically induced lift or subsidence that would act to enhance or inhibit convection, respectively.

Given this reasoning, the eastern Caribbean region does not exhibit any climatological differences with its surrounding environment in terms of conditions 1, 2, 4, and 5. Therefore, this study investigated the contributions of conditions 3 and 6 on the tropical cyclogenesis potential in the eastern Caribbean. Namely, the objectives of this study were to identify any possible sources of vertical wind shear in the lower troposphere and to see if there is any climatologically persistent impediment to buoyant instability, such as atmospheric subsidence.

HISTORICAL CONTEXT. As illustrated in Fig. 4, the eastern Caribbean domain was defined for this study to be the area bounded meridionally by 12.5° and 17.5°N and zonally by 75° and 60°W. The National Hurricane Center/Atlantic Oceanographic and Meteorological Laboratory/ Hurricane Research Division’s HURDAT best-track data for Atlantic tropical cyclones (www.aoml.noaa.gov/hrd/hurdat/) was used to extract genesis points from the 1851–2005

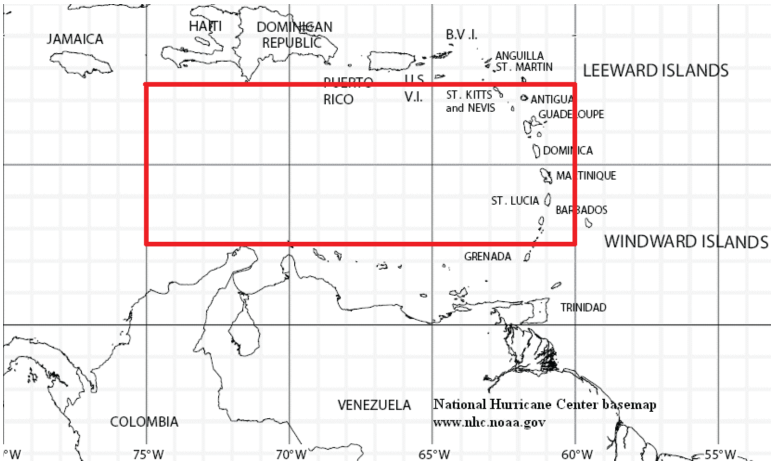

Fig. 4. Eastern Caribbean domain of study: 12.5°–17.5°N and 60°–75°W.

period. During this time, there were 1,353 tropical cyclones that reached a peak intensity of tropical storm or hurricane. Those cyclones that only reached a maximum classification of tropical depression were not included in the HURDAT file. Please note that locations of tropical cyclogenesis may not have been accurate prior to the satellite era, with a bias toward areas near land. However, given the relatively "land locked" location of the eastern Caribbean, with land to the north, south, and east, it is assumed that any tropical cyclones that formed in that region would have been identified even without satellite detection. It is further assumed that most convection embedded in the deep easterlies would affect the Leeward and Windward Islands prior to entering the eastern Caribbean. By including this early portion of the data, a frequency bias may be introduced, favoring the Caribbean. However, this was included for the sake of a larger sample size. However, even with this potential bias, it is clear from the results that a local minimum of tropical cyclogenesis exists in the eastern Caribbean.

The Atlantic hurricane season lasts from June to November and will heretofore be referred to as the "hurricane season." Out of the 1,353 tropical cyclones (including those that developed outside of the hurricane season) in the HURDAT database that formed in the Atlantic basin from 1851 to 2005, only 46 of them (3.4%) have developed over the eastern Caribbean. When compared to the 123 (9.1%) tropical cyclones that have developed over the northwestern Caribbean of roughly the same domain size (defined here to be between 15° and 20°N and between 75° and 90°W) and the 119 (8.8%) that have developed over the deep Atlantic (between 12.5° and 17.5°N and between 45°and 60°W) just east of the eastern Caribbean, it is clear that there is a relative minimum of genesis points over the eastern Caribbean. The 46 tropical cyclones that have formed over the eastern Caribbean are distributed with a peak in the month of September (Fig. 5a). At first glance, this appears to be similar to the tropical cyclogenesis frequency distribution for the Atlantic basin as a whole. However, it is crucial to notice that the distribution is skewed left, with greater frequency to the right. Thus, there is a greater frequency of tropical cyclones that form over the eastern Caribbean during the latter part of the hurricane season as opposed to the earlier part. This is more clearly seen when compared with a similar graph of genesis frequency over the deep Atlantic domain (Fig. 5b) as defined earlier (excluding one tropical cyclone that formed in December), where the peak is a bit earlier than the eastern Caribbean. In addition, given that the Caribbean as a whole exhibits a bimodal distribution of tropical cyclogenesis, with peaks in June and October (Inoue et al. 2002), the observed distribution for the eastern Caribbean is unique with respect to just one peak toward the latter part of the hurricane season. There must, therefore, be an inhibiting factor in the eastern Caribbean during the early part of the hurricane season to prevent that region from having a similar distribution as the rest of the Caribbean.

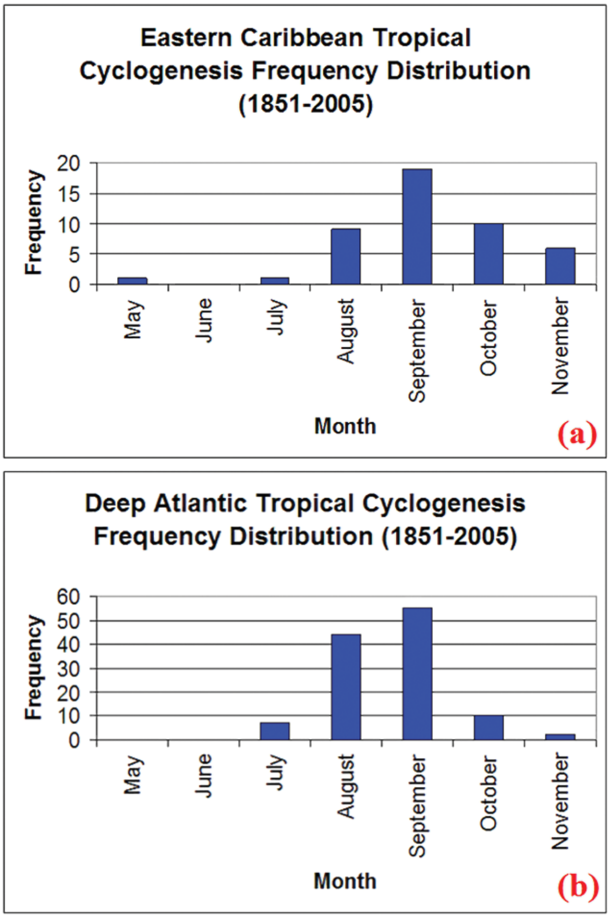

Fig. 5. Tropical cyclogenesis frequency distribution (1851–2005 by month) of the (a) eastern Caribbean (12.5°–17.5°N, 60°–75°W) and (b) deep Atlantic (12.5°–17.5°N, 45°–60°W), by month from 1851 to 2005. Notice the greater relative frequency toward the latter part of the hurricane season in the eastern Caribbean compared with that of the deep Atlantic.

ANALYSIS OF WIND FIELDS. Quick Scatterometer (QuikSCAT)-derived surface wind vectors over the Caribbean Sea were initially used to obtain a general diagnosis of the wind field. As shown in Fig. 6a, the July mean wind magnitudes exhibit a maximum in the central Caribbean. This particular

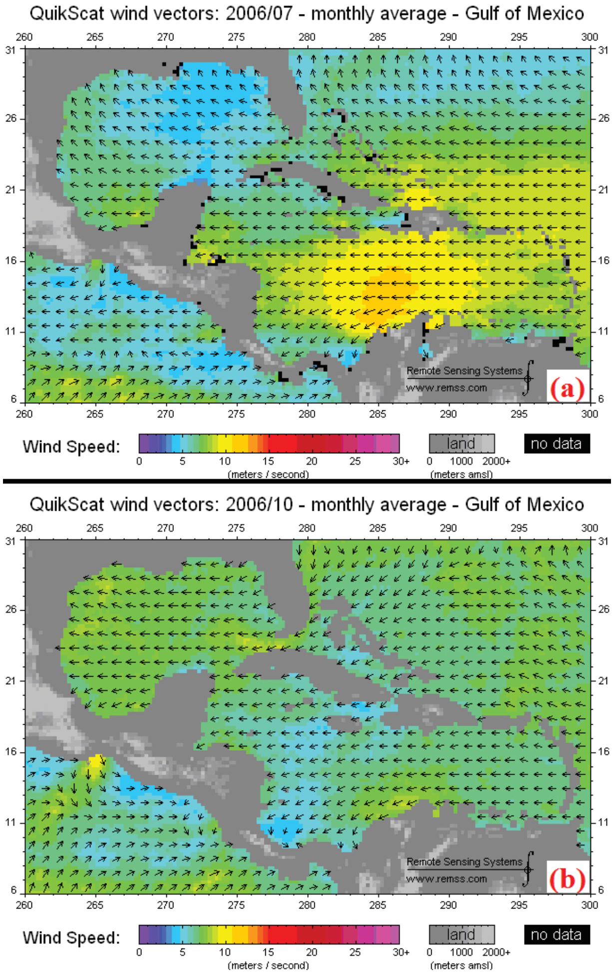

Fig. 6. QuikSCAT monthly-mean wind data for (a) Jul and (b) Oct 2006. Notice the strength of the CLLJ in the central Caribbean in Jul, and its substantial weakening by October. Arrows show only wind direction. Magnitude is depicted by the shades of color.

figure shows the mean for July 2006, which was selected as a representative example. Other years exhibit a similar phenomenon. This maximum in the surface easterlies is a manifestation of the Caribbean low-level jet (CLLJ; Wang and Enfield 2003). Within the context of the hurricane season, this feature is observed to be at its strongest toward the beginning of the season and weakening thereafter. It is clear from Fig. 6b that the October 2006 mean wind magnitudes for the central Caribbean are substantially weaker, and that the CLLJ effectively disappears toward the latter half of the hurricane season.

The acceleration of the surface easterlies over the central Caribbean would imply a region of horizontal surface speed divergence in the eastern Caribbean. To investigate this possibility, the NCEP–NCAR reanalysis data at 2.5° × 2.5° spatial resolution and 6-hourly time resolution (0000, 0600, 1200, and 1800 UTC) were used for this study. Monthly means as provided by the reanalysis were based on the 1968–96 period. However, for the statistical calculations within this study, the daily data from 1948 to 2004 were used to provide a larger sample size. Cross sections through the 17 pressure levels of the reanalysis horizontal wind field (calculated using the u and v wind fields) show that the CLLJ maximizes below the 850-hPa level, which is consistent with Wang and Enfield (2003). Also, given that tropical wave amplitudes often maximize between 850 and 950 hPa (Thorncroft and Hodges 2001), the 925-hPa level of the reanalysis was selected for further investigation.

Reanalysis monthly means (1968–96) of u and v wind fields were used to calculate climatological divergence values within the eastern Caribbean domain. These were plotted using the Graphical Analysis and Display System (GrADS) and compared to QuikSCAT images to assess the qualitative relationship between the eastern Caribbean divergence field and the strength of the CLLJ in the central Caribbean.

June and July (Figs. 7a,b) show a local maximum of mass divergence at 925 hPa south of Hispaniola. The divergence maximum climatologically shifts east and weakens as the hurricane season progresses (Figs. 7c–f). This is consistent with the seasonal decrease in the strength of the CLLJ as initially inferred from QuikSCAT. This deceleration in the central Caribbean surface easterlies toward the latter part of the hurricane season is resolved by the u and v wind fields of the reanalysis and is reflected by the decrease in divergence over the eastern Caribbean.

Calculations of divergence based on the 6-hourly reanalysis u and v wind fields (1948–2004) show the same result. The spatially and monthly averaged divergence values in the eastern Caribbean decrease from June to November (Table 1). In fact, the mean divergence values in the domain decrease by at least

Table 1. Monthly-mean 925-hPa divergence (s^{-1}) values averaged over the eastern Caribbean domain from 1948 to 2004. Notice the decreasing values as the hurricane season progresses.

Month	Mean 925-hPa divergence (s^{-1})
Jun	1.82×10^{-6}
Jul	1.36×10^{-6}
Aug	6.46×10^{-7}
Sep	1.07×10^{-7}
Oct	-8.59×10^{-8}
Nov	1.54×10^{-7}

an order of magnitude by September, October, and November. A statistical test was performed to determine the significance of this seasonal decrease. To do so, monthly means were computed, and a statistical unpaired hypothesis test for a difference of the mean divergence between the earlier and latter parts of the hurricane season, assuming independence (Wilks 2006), was carried out. The mean divergence values that were tested were those of months June and July considered together versus that of the months October and November. By comparing the first two and the last two months of the hurricane season, the sample size effectively becomes 114 (57 yr × 2 months) for each of the means.

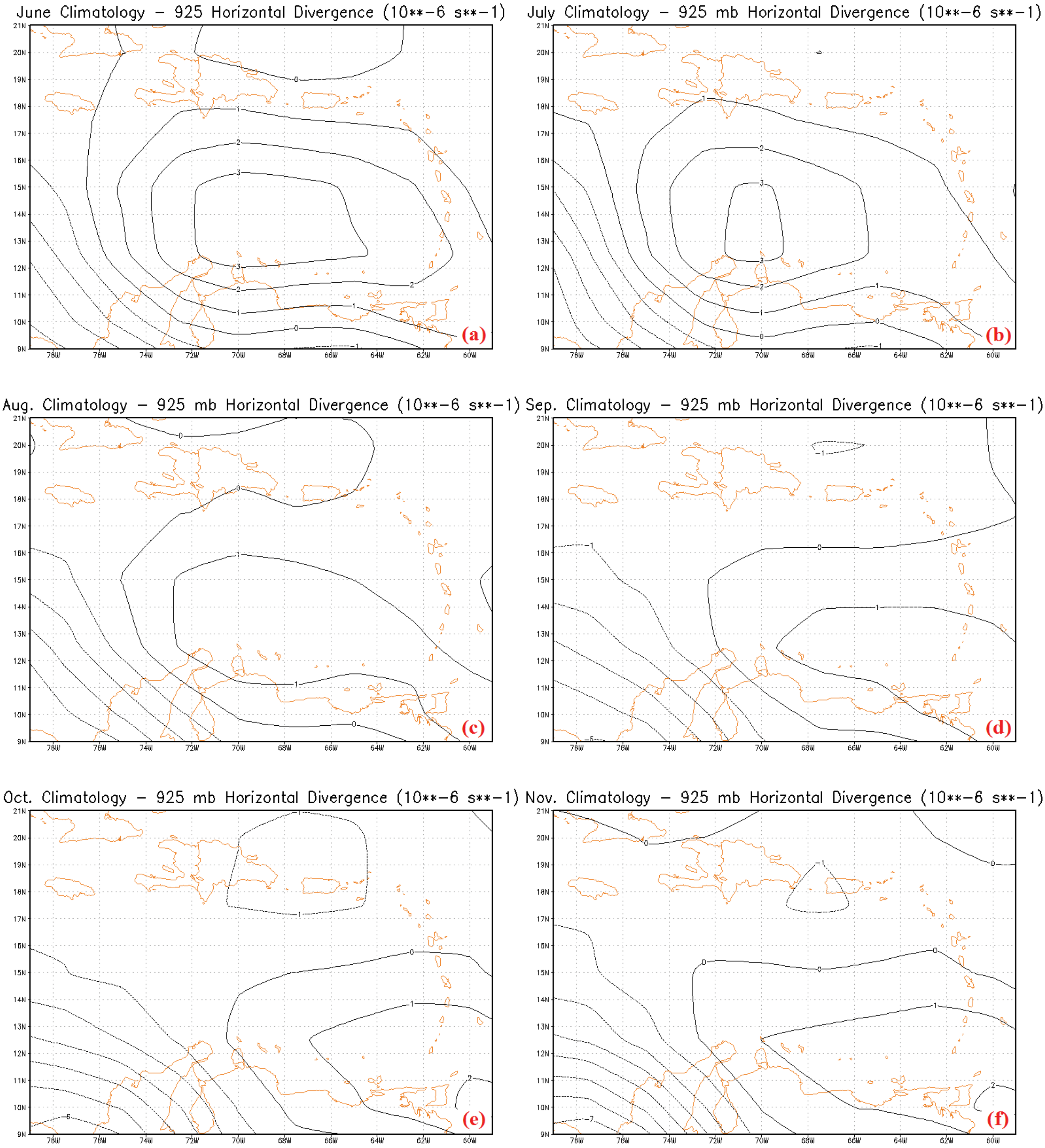

Fig. 7. Horizontal divergence [10^{-6} s^{-1}] climatology at 925 hPa for (a) Jun, (b) Jul, (c) Aug, (d) Sep, (e) Oct, and (f) Nov. Notice that the divergence values climatologically decrease toward the latter part of the hurricane season, consistent with the variation of the CLLJ.

The results showed a z score of 18.7 and a p value of roughly zero. Therefore, it can be confidently asserted that the mean eastern Caribbean divergence at 925 hPa decreases throughout each hurricane season. Figure 8a shows an extended time series of the divergence values averaged by month from 1948 to 2004. It is clear that the monthly divergence is periodic within each hurricane season, whereas the underlying mean value has remained roughly constant throughout the 57-yr period. This periodicity can be seen more clearly in Fig. 8b, which is an arbitrary selection of the most recent decade to show the intrahurricane seasonal fluctuation of divergence.

SEASONAL VARIATIONS. The fact that tropical cyclogenesis is less inhibited over the eastern Caribbean toward the latter part of the hurricane season coincides with the climatological decrease of low-level divergence in the eastern Caribbean. When the genesis frequencies over the northwestern Caribbean are graphed (Fig. 9), excluding one tropical cyclone that formed in February, the approximately bimodal distribution described by Inoue et al. (2002) can be seen, given that the overall Caribbean distribution is weighted toward the higher genesis frequencies over the northwestern Caribbean. It should be no coincidence that the initial genesis peak in June for the northwest Caribbean is in phase with the enhanced low-level convergence present in the exit region of the CLLJ. This coincides with the relative absence of genesis in the eastern Caribbean at the same time (Fig. 5a), when the CLLJ is strong with the divergent entrance region positioned over the eastern Caribbean.

As the CLLJ weakens toward the latter part of the hurricane season, tropical cyclogenesis over the eastern Caribbean becomes less inhibited, so the frequencies increase. Therefore, it can be said that the presence of a strong CLLJ in the early part of the season will favor tropical cyclogenesis over the northwestern Caribbean and inhibit tropical cyclogenesis over the eastern Caribbean. However, because there are other factors involved with tropical cyclogenesis over the Caribbean beyond the effects of the CLLJ, it is important to note that the exact opposite may not be true when the CLLJ is weaker. A weak CLLJ may not necessarily imply increased cyclogenesis frequencies over the eastern Caribbean and lower frequency over the northwestern Caribbean. This is important when considering the presence of the second peak in October over the northwestern Caribbean. Both the northwestern and eastern Caribbean show increased tropical cyclogenesis frequencies toward the latter part of the hurricane season. It can, therefore, be concluded that the effects of the CLLJ may only be present toward the earlier part of the hurricane season when it is strong and toward that latter part of the season when it is weak; its effects become negligible when compared with other factors that govern tropical cyclogenesis. In addition, as suggested by Inoue et al. (2002), the lull in genesis activity in the month of July may be due to more complicated ocean–atmosphere processes that extend beyond the surface divergence–convergence wind flow patterns associated with the strength of the CLLJ.

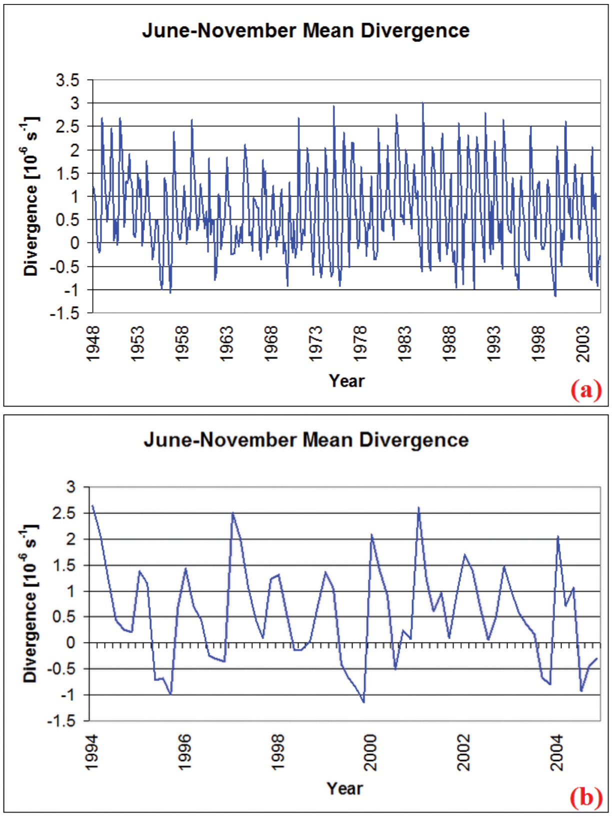

FIG. 8. Jun through Nov time series of eastern Caribbean domain-averaged divergence (s^{-1}) values (a) from 1948 to 2004 and (b) from 1994 to 2004. Notice the cycle of decreasing divergence values throughout each hurricane season. Also notice that (a),(b) only include data from Jun through Nov of each year. The divergence values from Dec to May are ignored to emphasize the decrease of divergence during the hurricane seasons. Therefore, each year has a total of six data points. The Nov data point of a given year is connected in the time series to the Jun data point of the following year to provide continuity and to express the periodic nature of the divergence values.

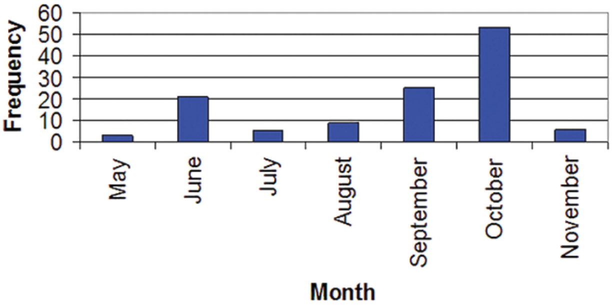

Fig. 9. Tropical cyclogenesis frequency distribution (1851–2005 by month) of the northwestern Caribbean (between 15° and 20°N and between 75° and 90°W). Notice the secondary, early season peak in the northwestern Caribbean, which may be a reflection of the enhanced surface convergence provided by the exit region of the CLLJ.

EFFECTS FROM EL NIÑO–SOUTHERN OSCILLATION (ENSO). Because there is a relationship between eastern Caribbean tropical cyclogenesis potential and the strength of the CLLJ over the central Caribbean, it is of interest to investigate possible climatological teleconnections that may affect the strength of the CLLJ. According to Wang and Enfield (2003) and Wang et al. (2006), El Niño during the boreal winter weakens the North Atlantic subtropical high (NASH), but it has an opposite effect during the winter and summer. This implies that El Niño during the summer strengthens the NASH and therefore strengthens the CLLJ. Reasons for this reversal in relationship are unclear. Given the complex relationships between the global climatological factors that may affect the strength of the CLLJ, we agree with Wang (2007) that future numerical modeling efforts will be necessary to identify the relative magnitudes of the contributions of each of the factors. However, based on the divergent wind anomalies calculated by Wang and Enfield (2003), we suggest that the sign reversal of the correlation between El Niño and the NASH in the winter versus the summer is likely due to the migration of the upward branch of the Hadley cell from the Amazon in the winter to the Gulf of Mexico and northwest Caribbean in the summer, in response to the Atlantic warm pool (AWP). Therefore, when El Niño occurs in the summer, the upward branch of the Walker circulation opposes the southern, subsident branch of the Hadley cell over the AWP. This would then weaken the Hadley cell, raise sea level pressures over the AWP, and the NASH would intensify, leading to a stronger CLLJ. This would explain Wang and Enfield's (2003) observation that El Niño intensifies the CLLJ during the summer. Again, numerical modeling efforts would need to be undertaken to quantify the various climatological contributions to the strength of the CLLJ.

The fact that El Niño in the summer intensifies the CLLJ suggests that divergence values over the eastern Caribbean should have a positive correlation with the intensity of El Niño during the summer months. To investigate this relationship, the 1951–2004 Southern Oscillation index (SOI) anomalies, calculated with respect to departures from the 1951–80 base period provided by the Climate Prediction Center, were correlated by month with the mean monthly divergence values during those years. Correlations at 0 lag between the monthly divergence values and the SOI are shown in Table 2. All of the months show a negative correlation, which imply that divergence over the eastern Caribbean becomes more positive as SOI becomes more negative during the hurricane season, especially during the earlier months of the season. This is consistent with the previous assertion that there is a positive correlation between the intensity of El Niño in the summer and the intensity of the CLLJ. However, it must be emphasized that whereas El Niño events are typically associated with a negative SOI, one cannot automatically infer that a negative SOI implies El Niño. Indeed, with the SOI being susceptible to noise, various filters must be imposed with other variables taken into consideration to determine whether El Niño can be declared for a certain period of time. This is beyond the scope of this study, but statistical calculations to test the correlation of SOI with monthly divergence values in the eastern Caribbean still yield useful results.

Assuming a Gaussian distribution of the Fisher Z transformation (Wilks 2006), where Z is defined as follows:

$$Z = \frac{1}{2}\ln\left[\frac{1+r}{1-r}\right],$$

Table 2. Correlation coefficients (0 lag) between the monthly-mean 925-hPa divergence values averaged over the eastern Caribbean domain and the SOI from 1951 to 2004.

Month	0-lag *r* monthly divergence vs SOI
Jun	−0.39
Jul	−0.46
Aug	−0.61
Sep	−0.36
Oct	−0.39
Nov	−0.13

all of the correlations are significant at the 1% level with the exception of $r = -0.13$ for November. This can be explained by the fact that November is the transition period into the winter season, where the effects of El Niño upon the strength of the CLLJ are opposite that of summer (Wang 2007). However, because there is a significant correlation between the SOI and eastern Caribbean divergence at 925 hPa during most of the hurricane season, it can be confidently stated that negative values of SOI during the hurricane season will reduce the likelihood of tropical cyclogenesis in the eastern Caribbean through the low-level divergence-inducing CLLJ. If the condition of El Niño can be established, Tang and Neelin (2004) identified another inhibiting effect it can have on Atlantic tropical cyclogenesis via the warming and stabilization of the Atlantic tropical troposphere.

Finally, a likelihood ratio test (Wilks 2006) was conducted to see whether the probabilities of tropical cyclogenesis over the eastern Caribbean in any given year can be described by two separate Poisson distributions (negative SOI months and positive SOI months) with different means. The test statistic that was used for the likelihood ratio test is as follows:

$$\Lambda^* = 2\ln\left[\frac{\Lambda(H_A)}{\Lambda(H_0)}\right] = 2\left[L(H_A) - L(H_0)\right].$$

Here, $\Lambda(H_0)$ is the likelihood function associated with the null hypothesis (H_0), and $\Lambda(H_A)$ is the likelihood function associated with the alternative hypothesis (H_A). Function L is the log-likelihood as defined by Wilks (2006). Because the sampling distribution of Λ^* can be described by the χ^2 distribution, this statistic was used to test whether the probability distribution of tropical cyclogenesis over the eastern Caribbean during negative SOI months is significantly different from that of positive SOI months.

A likelihood ratio test comparing the Poisson distributions of tropical cyclones that form in the eastern Caribbean during negative SOI months with that of positive SOI months suggests that the null hypothesis of equal distribution can be rejected at roughly the 20% significance level ($\chi^2 \approx 1.6$ with df = 1). The result of this test is not as strong as a test with a traditional rejection at the 10% significance level, but it must be noted that only the period 1951–2004 was considered with respect to the SOI dataset from the Climate Prediction Center. The event of tropical cyclogenesis over the eastern Caribbean is so rare (with only 10 cases within this period), that even a sample size of 324 months produces a very small Poisson mean for both categories that are compared. However, it is simply worth noting that there is some evidence to suggest that the Poisson mean of tropical cyclogenesis frequencies during positive SOI months is indeed higher than that of negative SOI months.

El Niño is already known to negatively affect the development of tropical cyclones in the Atlantic basin through an increase in vertical wind shear (Gray 1984). However, it must be noted that because the relative frequencies of tropical cyclogenesis over the eastern Caribbean are inversely related to the magnitude of the low-level divergence in the region, it can be concluded that El Niño will further act to inhibit tropical cyclogenesis over the eastern Caribbean through dynamically induced subsidence in addition to the large-scale increase in vertical wind shear throughout the Atlantic basin. Further supporting this argument is Wang's (2007) finding that the CLLJ's contribution to vertical wind shear is only significant over the southwestern Caribbean. Therefore, the CLLJ contributes to the inhibition of convective development and tropical cyclogenesis through the enhanced subsidence in the vertical column over the eastern Caribbean by mass conservation. Wang (2007), referring to the entire Caribbean region as a whole, suggests that "the easterly CLLJ increases the moisture flux divergence in the Caribbean and thus suppresses the convection, decreasing rainfall and suppressing the formation of tropical cyclones." Although this may be true and there is a bimodal distribution of tropical cyclogenesis in the Caribbean (Inoue et al. 2002), there is still a local minimum of tropical cyclogenesis over the eastern Caribbean relative to the rest of the Atlantic basin. Therefore, the argument in this study for subsidence and low-level divergence being a factor against cyclogenesis in the eastern Caribbean still holds. It is also likely that the CLLJ interacts with the SSTs and upper-level wind field to create additional unfavorable conditions for tropical cyclogenesis in this region (Knaff 1997; Inoue et al. 2002).

What have we learned? The major findings of this study are as follows:

- The CLLJ is a semipermanent feature in the central Caribbean that plays an active role in tropical cyclogenesis potential in the eastern Caribbean. The CLLJ is an area of accelerating low-level easterlies that maximize at 925 hPa and create an area of divergence at the same level in the eastern Caribbean, which induces subsidence in the vertical column by mass conservation. This inhibits the intensification of convection and discourages tropical cyclogenesis. The easterlies can also force open water upwelling and enhance the vertical shear, further inhibiting cyclogenesis.

- The intensity of the CLLJ and the magnitude of the divergence over the eastern Caribbean vary intraannually, with a maximum in July and a steady decrease throughout the hurricane season.
- The relative frequencies of tropical cyclogenesis over the eastern Caribbean during the 1851–2005 period exhibit a peak in September. However, the distribution is skewed left, favoring higher probabilities of tropical cyclone formation in the latter part of the hurricane season. This is consistent with the seasonal decrease in low-level divergence in the eastern Caribbean.
- Negative SOI values during the hurricane season, with the exception of November, are significantly correlated with the magnitude of low-level divergence over the eastern Caribbean. Thus, negative SOI conditions discourage tropical cyclogenesis over the eastern Caribbean through the CLLJ, among other factors. However, physical connections between ENSO and CLLJ variability have yet to be quantified.

The exact source of the CLLJ variability is still somewhat unknown due to the many complex climate teleconnections that influence it (Wang 2007). In addition to what has been discussed earlier, it has been suggested that there is a relationship between the CLLJ and the onset of the midsummer drought in Central America and Mexico (Magaña et al. 1999). The variability of the CLLJ was described from an observational perspective in Wang (2007). In this present study, the CLLJ's effect on eastern Caribbean tropical cyclogenesis was investigated. The next step to improve understanding of this phenomenon would be to isolate the most significant conditions that force the CLLJ's variability, which would best be done through numerical modeling. In addition, the climatological divergence patterns associated with CLLJ variability in nearby regions such as the western Caribbean should be studied to see if there is a relationship with the observed tropical cyclogenesis frequency distribution for that region. The 16 July 2004 case presented in this paper clearly showed an area of preexisting low-level divergence and midtropospheric subsidence ahead of the convection (Figs. 2c,d), so the climatological divergence signature reflected in the NCEP–NCAR reanalysis can be considered a cause, rather than the effect, of weakening convection over the eastern Caribbean. However, it would be beneficial to investigate more individual cases of developing and nondeveloping tropical disturbances in a future study.

The precise mechanism(s) by which the CLLJ inhibits tropical disturbances would need to be explored in a coupled atmosphere–ocean numerical model. Although we have hypothesized that the mechanism is the CLLJ-related divergence and associated subsidence, it could also be CLLJ-induced upwelling or vertical shear, or some combination of these factors.

By identifying low-level divergence and subsidence as one of the causes for the local minimum of tropical cyclogenesis over the eastern Caribbean Sea, this study sheds light on the mystery of the "hurricane graveyard" of the Atlantic. In actuality, this term is a misnomer, as major hurricanes do not seem to be affected by the region of low-level divergence. A strong cyclone usually exhibits large convergence at low-levels that overwhelms the preexisting area of divergence. For example, Hurricane Ivan (2004) traversed the region seemingly unaffected. Only weaker systems—such as weak tropical storms, tropical depressions, and tropical disturbances—pose this unique intensity forecasting challenge over the eastern Caribbean. DeMaria (1996) has shown that vertical shear, in this situation associated with the divergent easterly flow, preferentially affects small, relatively weak systems at low latitudes. That the divergent region over the eastern Caribbean is related to the intensity of the CLLJ on a monthly basis implies that the divergence maximum in the NCEP–NCAR reanalysis is a preexisting, climatological phenomenon rather than a reflection of the dissipation of convection in that region as a result of some other unknown factor.

IMPLICATIONS FOR FORECASTING.

Because of the land-locked geography of the Caribbean Sea, residents of the surrounding nations depend on accurate tropical cyclone track and intensity forecasts. And, because this region is often a breeding ground for tropical disturbances and tropical cyclones, these forecasts are contingent upon the correct understanding of tropical cyclogenesis potential. The eastern Caribbean is especially important because climatologically, paths of tropical cyclones that enter the Caribbean Sea threaten land areas, including the United States.

The results of this study suggest that forecasters should take into account the magnitude of the preexisting low-level divergence field ahead of any tropical disturbance entering the eastern Caribbean. A qualitative measure of this in real time may be gained through the analysis of the strength of the CLLJ over the central Caribbean. If numerical model forecasts are used for guidance, then care must be taken to ensure that the model runs are initialized properly with an accurate representation of the low-level wind field over the Caribbean Sea surrounding the tropical disturbance of interest.

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REFERENCES

Avila, L., cited 2000: Tropical Depression Joyce discussion 25. [Available online at www.nhc.noaa.gov/archive/2000/dis/NAL1400.025.html.]

DeMaria, M., 1996: The effect of vertical shear on tropical cyclone intensity change. *J. Atmos. Sci.,* **53,** 2076–2088.

Dunion, J. P., and C. S. Velden, 2004: The impact of the Saharan air layer on Atlantic tropical cyclone activity. *Bull. Amer. Meteor. Soc.,* **85,** 353–365.

Fitzpatrick, P. J., J. A. Knaff, C. W. Landsea, and S. V. Finley, 1995: Documentation of a systematic bias in the aviation model's forecast of the Atlantic tropical upper-tropospheric trough: Implications for tropical cyclone forecasting. *Wea. Forecasting,* **10,** 433–446.

Goldenberg, S. B., and L. J. Shapiro, 1996: Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity. *J. Climate,* **9,** 1169–1187.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96,** 669–700.

——, 1984: Atlantic seasonal hurricane frequency. Part I: El Niño and 30-mb quasi-biennial oscillation influences. *Mon. Wea. Rev.,* **112,** 1649–1668.

Hennon, C. C., and J. S. Hobgood, 2003: Forecasting tropical cyclogenesis over the Atlantic basin using large-scale data. *Mon. Wea. Rev.,* **131,** 2927–2940.

Henry, A. J., 1924: Mitchell on West Indian hurricanes and other tropical cyclones of the North Atlantic Ocean. *Mon. Wea. Rev.,* **52,** 446–447 pp.

Inoue, M., I. C. Handoh, and G. R. Bigg, 2002: Bimodal distribution of tropical cyclogenesis in the Caribbean: Characteristics and environmental factors. *J. Climate,* **15,** 2897–2905.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Knaff, J. A., 1997: Implications of summertime sea level pressure anomalies in the tropical Atlantic region. *J. Climate,* **10,** 789–804.

Magaña, V., J. A. Amador, and S. Medina, 1999: The midsummer drought over Mexico and Central America. *J. Climate,* **12,** 1577–1588.

Tang, B. H., and J. D. Neelin, 2004: ENSO influence on Atlantic hurricanes via tropospheric warming. *Geophys. Res. Lett.,* **31,** L24204, doi:10.1029/2004GL021072.

Thorncroft, C. D., and K. Hodges, 2001: African easterly wave variability and its relationship to Atlantic tropical cyclone activity. *J. Climate,* **14,** 1166–1179.

Wang, C., 2007: Variability of the Caribbean Low-Level Jet and Its Relations to Climate. *Climate Dyn.,* **29,** 411–422.

——, and D. B. Enfield, 2001: The tropical Western Hemisphere warm pool. *Geophys. Res. Lett.,* **28,** 1635–1638.

——, and ——, 2003: A further study of the tropical Western Hemisphere warm pool. *J. Climate,* **16,** 1476–1493.

——, and ——, S. Lee, C. W. Landsea, 2006: Influences of the Atlantic warm pool on Western Hemisphere summer rainfall and Atlantic Hurricanes. *J. Climate,* **19,** 3011–3028.

Wilks, D. S., 2006: *Statistical Methods in the Atmospheric Sciences.* 2nd ed. Elsevier Academic Press, 627 pp.