Local Minimum of Tropical Cyclogenesis in the Eastern Caribbean

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ABSTRACT

The study has determined that a local, climatological minimum of tropical cyclogenesis exists over the eastern Caribbean Sea. This area, known colloquially by forecasters as the "hurricane graveyard," is located within the belt of tropical easterlies during most of the Atlantic hurricane season, which lasts from June through November. Tropical easterly waves emerging from the African continent usually follow a path through the Lesser Antilles and into the eastern Caribbean. GOES infrared satellite imagery shows that easterly waves frequently exhibit warming cloud tops and decreasing convection in an area bounded by the islands to the north and east, Venezuela to the south, and roughly 75 degrees longitude to the west. QuikSCAT derived surface winds during clear-sky conditions frequently show the presence of accelerating easterlies in the central Caribbean as part of the Caribbean Low-Level Jet (CLLJ). Analysis of the NCEP global reanalysis wind fields suggests the presence of an area of persistent low-level mass divergence in the eastern Caribbean. This implies a subsident regime that would weaken convection. Climatologically, this phenomenon reaches peak intensity in July, then shifts towards the east and weakens in the latter half of the Atlantic hurricane season. This is reflected by the local minimum of tropical cyclogenesis points in the National Hurricane Center's best track data in the early part of the season. El Niño directly affects the strength of the CLLJ, and hence, is related to the intensity of the low-level divergence in the eastern Caribbean. The local minimum of tropical cyclogenesis in this region has important implications to operational forecasting, since the vast majority of tropical cyclones in the Caribbean eventually affect surrounding landmasses.

1. Introduction

Hurricane forecasters have long been puzzled 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 in the North Atlantic Ocean. Oftentimes, these surface atmospheric waves or weak tropical cyclones and their associated convection unexpectedly decrease in intensity in the eastern Caribbean, only to redevelop once they enter the western Caribbean, posing a dilemma for forecasters.

An example of a tropical disturbance that weakened upon entering the eastern Caribbean can be seen in Fig. 1a and Fig. 1b. Fig. 1a shows the disturbance at 0015Z on July 16, 2004 with healthy convection just west of the Lesser Antilles. However, only three hours later (Fig. 1b), the convection collapsed.

For years, the National Hurricane Center has colloquially referred to this eastern Caribbean region as a hurricane graveyard. A good example of this 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).

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. Due to 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 re-intensification once it leaves the region. This study investigates the possible climatological factors that may be contributing to this local minimum of tropical cyclogenesis. Since 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 may be contributing to the unexpected weakening of nascent tropical cyclones in the eastern Caribbean.

2. Background

The conditions supportive of tropical cyclogenesis are generally well understood. These conditions are summarized by Hennon and Hobgood (2003) as: (1) a persistent area of convection, (2) sufficient planetary vorticity, (3) little to no vertical wind shear, (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 significant phenomenon, there must be some condition that is climatologically persistent that tends to contribute toward tropical cyclolysis. It is obvious that conditions (1), (2), (4), and (5) above are not of concern for this study. The persistence of convection is itself the topic of study, as convection is often observed to weaken unexpectedly in 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, since the region is embedded within the deep tropics with prevailing surface easterlies advecting moisture from a generally uniform moisture source – the tropical 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 while 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, 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 shown from satellite data that the eastern Caribbean Sea does not exhibit significant departures in sea surface temperatures (SST) 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 "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 due to upwelling by the easterlies in the southwestern Caribbean Sea (Inoue et al. 2002), but that is outside the geographic domain of this study.

Finally, it is necessary to address the remaining two conditions that favor tropical cyclogenesis: (3) little to no vertical wind shear and (6) 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. There is no evidence that would suggest that the eastern Caribbean region is more likely to experience the temporal, synoptic-scale intrusions of upper-level westerlies from the mid-latitudes, since the region is sub-synoptic scale. Hence, any increase in vertical wind shear would most likely result from accelerations in the low-level easterlies. Condition (6) can be broadly inferred to include mechanisms that cause vertical motion. The presence of lift or subsidence would act to enhance or inhibit convection, respectively.

Given the above discussion, the eastern Caribbean region does not exhibit any significant 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 objective of this study was 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.

3. Data and Methodology

Maps with the QuikSCAT satellite-derived surface wind speeds over the Caribbean Sea were used for the initial observational phase of this study. As shown in Fig. 2a, the July mean wind magnitudes exhibit a maximum in the central Caribbean. This particular figure shows the mean for July 2006, which was selected as a representative example. Other years exhibit the same 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 June-November Atlantic hurricane season, this feature is observed to be at its strongest during the beginning, then weakening as the months progress. It is clear from Fig. 2b that the October 2006 mean wind magnitudes for the central Caribbean are substantially weaker. The CLLJ effectively disappears towards the latter half of the hurricane season.

The acceleration of the surface easterlies in 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° x 2.5° degree spatial resolution and 6 hourly time resolution (00Z, 06Z, 12Z, and 18Z) were used for this study. Monthly means as provided by the Reanalysis were based on the 1968 to 1996 time 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 mb level, which is consistent with Wang and Enfield (2003). Also, given that tropical wave amplitudes often maximize between 850 mb and 950 mb (Thorncroft and Hodges 2001), the 925 mb level of the Reanalysis was selected for further investigation.

As illustrated in Fig. 3, the eastern Caribbean domain was defined for this study to be the area bounded meridionally by 17.5° N and 12.5° N and zonally by 75° W and 60° W. Reanalysis monthly means of u- and v-wind fields were used to calculate climatological divergence values within the 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.

For the purpose of quantitative analyses, the 6-hourly Reanalysis data from 1948 to 2004 were used to calculate the divergence values averaged over the spatial domain defined above. Monthly means were then computed, and a statistical unpaired hypothesis test for a difference of the mean divergence between the beginning and the latter part of the hurricane season, assuming independence (Wilks 2006), was performed. The mean divergence values that were tested were those of the June and July months considered togetehr versus that of the October and November months. By comparing the first two and the last two months of the hurricane season, the sample size effectively becomes 114 (57 years x 2 months) for each of the means. Findings of this test as well as others mentioned in this section will be discussed in the following section.

The National Hurricane Center/AOML Hurricane Research Division HURDAT best-track data for Atlantic tropical cyclones was used to extract genesis points from the 1851 to 2005 time period. During this time, there were 1353 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 towards 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. This would be assisted by the fact that most convection embedded in the deep easterlies would affect the Leeward and Windward islands prior to entering the eastern Caribbean.

The Southern Oscillation Index anomalies (1951 to 2004) provided by the Climate Prediction Center were correlated by month with the divergence values during those years. The results suggest that there may be large-scale climatological teleconnections that may play a role in tropical cyclogenesis potential in the eastern Caribbean.

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

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

Here, $\Lambda(\mathrm{H_0})$ is the likelihood function associated with the null hypothesis ($\mathrm{H_0}$), and $\Lambda(\mathrm{H_A})$ is the likelihood function associated with the alternative hypothesis ($\mathrm{H_A}$). Function L is the log-likelihood as defined by Wilks (2006). Since 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 in the eastern Caribbean during El Niño conditions is significantly different from that of non-El Niño months.

4. Results and Discussion

The calculations performed on the Reanalysis monthly means (1968 to 1996) for June and July (Fig. 4a and 4b) show a local maximum of mass divergence at 925 mb just south of Hispaniola. The divergence maximum climatologically shifts east and weakens as the hurricane season progresses (Fig. 4c-4e). This is consistent with the seasonal decrease in the strength of the CLLJ. This deceleration in the central Caribbean surface easterlies towards the latter part of the Atlantic hurricane season is resolved by the u- and v-wind fields of the Reanalysis and is reflected by the decrease in divergence in the eastern Caribbean.

Quantitatively, the 6-hourly Reanalysis u- and v-wind fields (1948 to 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 divergence values decrease by at least an order of magnitude throughout the domain by September, October, and November. A statistical test was performed to determine the significance of this seasonal decrease. With a z-score of 18.7 and a p-value of roughly zero, it can be confidently concluded that the mean eastern Caribbean divergence at 925 mb decreases seasonally with respect to the Atlantic hurricane season. Fig. 5a 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, while the underlying mean value has remained roughly constant throughout the 57-year period. This periodicity can be seen more clearly in Fig. 5b, which is an arbitrary selection of the most recent decade to show the intra-hurricane season fluctuation of divergence. Please note that for both of these figures, the plots only include data from June through November of each year. The divergence values from December 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 November data point of a given year is connected in the time series to the June data point of the following year to provide continuity and express the periodic nature of the divergence values.

Out of the 1353 tropical cyclones, as defined by the HURDAT database, that formed in the Atlantic Basin from 1851 to 2005, only 46 of them (3.4%) have developed in the eastern Caribbean. When compared to the 123 (9.1%) that have developed in the northwest Caribbean of roughly the same domain size (defined here to be between 15°-20° N and 75°-90° W) and the 119 (8.8%) that have developed in the deep Atlantic just east of the eastern Caribbean (between 12.5°-17.5° N and 45°-60° W), it is clear that there is a relative minimum of genesis points in the eastern Caribbean. The 46 tropical cyclones that have formed in the eastern Caribbean are distributed with a peak in the month of September (Fig. 6). 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 note that the distribution is skewed left, with greater occurrence frequency to the right. There is a greater relative frequency of tropical cyclones that form in the latter part of the hurricane season as opposed to the initial part. In addition, given that the Caribbean as a whole exhibits a bimodal distribution of tropical cyclogenesis, with peaks in June and October (Inoue 2002), the observed distribution for the eastern Caribbean is unique with respect to just one peak towards the latter part of the hurricane season. The fact that tropical cyclogenesis is more favored in the eastern Caribbean towards the latter part of the hurricane season coincides with the climatological decrease of low-level divergence in the eastern Caribbean.

Since there is a relationship between eastern Caribbean tropical cyclogenesis potential and the strength of the CLLJ in the central Caribbean, it is of interest to investigate possible climatological teleconnections that may affect the strength of the CLLJ. According to Wang et al. (2003, 2006), El Niño in the boreal winter weakens the North Atlantic Subtropical High (NASH). This occurs via multiple tropospheric processes. During winters when El Niño is at its peak, the upward branch of the zonal Walker Circulation shifts eastward. In turn, the subsident branch on the eastern flank of the Walker Circulation shifts over the Amazon. This opposes the rising branch of the meridional Hadley Circulation that is usually centered on the Amazon during boreal winters. Since the Hadley Cell partially sustains the NASH, a weaker Hadley Cell would lead to a weaker NASH in the winter. This, in turn, intensifies the easterly trade winds over the North Atlantic, which increase evaporative cooling and upwelling in the Atlantic Basin, thereby leading to an enhanced Atlantic Warm Pool (AWP) the following summer. With the peak of the AWP occurring during the late summer and early fall, the rising branch of the Hadley Cell shifts over the northwest Caribbean and the Gulf of Mexico, providing negative sea-level pressure anomalies that weaken the southwestern edge of the NASH. Hence, El Niño in the winter serves to weaken the NASH in the winter as well as the following summer, through the positive feedback mechanism of an enhanced AWP. The strength of the CLLJ is positively correlated with the North Atlantic Oscillation

(NAO), which implies a relation to the strength of the NASH (Wang 2007). A stronger (weaker) NASH is associated with a stronger (weaker) CLLJ. Therefore, El Niño in the winter weakens the CLLJ in the winter.

According to Wang (2003, 2007), the effects of El Niño on the NASH are opposite during the winter and the summer. This implies that El Niño in 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 in Wang (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 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. These 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 (2003)'s 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 in the eastern Caribbean should have a positive correlation with the intensity of El

Niño during the summer months. Correlations at 0-lag between the monthly divergence values and the SOI (1951 to 2004) are shown in Table 2. All of the months show a negative correlation, which imply that divergence in the eastern Caribbean becomes more positive as SOI becomes more negative (stronger El Niño) during the hurricane season, especially during the earlier months of the hurricane season. This is consistent with the previously stated conclusion that there exists a positive correlation between the intensity of El Niño in the summer and the intensity of the CLLJ. Assuming a Gaussian distribution of the Fisher Z transformation (Wilks 2006), where Z is defined as follows:

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

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 of the fact that there is a significant positive correlation between El Niño intensity and eastern Caribbean divergence at 925 mb during most of the hurricane season, it can be confidently stated that El Niño during the hurricane season will reduce the likelihood of tropical cyclogenesis in the eastern Caribbean through the low-level divergence-inducing CLLJ.

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 one with a traditional rejection at the 10% significance level, but it must be noted that only the period 1951 to 2004 was considered with respect to the SOI anomaly dataset from the Climate Prediction Center. The event of tropical cyclogenesis in 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 marginally significant evidence to suggest that the Poisson mean of tropical cyclogenesis frequencies during non-El Niño months is indeed higher than that of El Niño months.

El Niño is already known to negatively affect the development of tropical cyclones in the Atlantic Basic through an increase in vertical wind shear (Gray 1984). However, it must be noted that since the relative frequencies of tropical cyclogenesis in 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 in the eastern Caribbean through local subsidence in addition to the large-scale increase in vertical wind shear throughout the Atlantic Basin. Further supporting this argument is Wang (2007)'s finding that the CLLJ's contribution to vertical wind shear is only significant in the southwestern Caribbean. Therefore, the primary contribution of the CLLJ to the inhibition of convective development (and cyclogenesis) is through the enhanced subsidence in the vertical column in the eastern Caribbean due to 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." While this may be true and that there is a bimodal distribution of tropical cyclogenesis in the Caribbean (Inoue et al. 2002), there is still a local minimum of tropical cyclogenesis in the eastern Caribbean. Therefore, the argument in this study for subsidence and low-level divergence being a primary factor against cyclogenesis in the eastern Caribbean still holds.

5. Summary and Conclusions

Long-term historical records of tropical cyclogenesis points suggest that there is a local minimum of tropical cyclogenesis frequencies in the eastern Caribbean Sea. Indeed, short-term satellite imagery often indicate the decay of convective activity associated with tropical disturbances embedded within the deep easterlies in the tropical Atlantic as they traverse the eastern Caribbean region. Of all of the conditions that inhibit tropical cyclogenesis, only one stands out to be climatologically persistent in the eastern Caribbean – subsidence. The major findings of this study are as follows:

- The CLLJ is a semi-permanent feature in the central Caribbean that plays an active roll in tropical cyclogenesis potential in the eastern Caribbean. The CLLJ is an area of accelerating low-level easterlies that maximize at 925 mb and creates 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 hence works against cyclogenesis.
- The intensity of the CLLJ and the magnitude of the divergence in the eastern Caribbean varies intra-annually, with a maximum in July and a steady decrease throughout the hurricane season.
- The relative frequencies of tropical cyclogenesis in the eastern Caribbean in 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.

- El Niño has a positive correlation with the strength of the CLLJ. Hence, El Niño in the summer (during the hurricane season with the exception of November) is significantly correlated with the low-level divergence in the eastern Caribbean. This is also reflected by the climatological records of more storms forming in the eastern Caribbean during months with negative SOI.

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 above, it has been suggested that there is a relationship between the CLLJ and the onset of the Mid-Summer Drought in central American and Mexico (Magaña 1999). The variability of the CLLJ was described from an observational perspective in Wang (2007). In this present study, the CLLJ's effects on eastern Caribbean tropical cyclogenesis is 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 efforts. 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 exists a relationship with the observed tropical cyclogenesis frequency distribution for that region.

By identifying low-level divergence and subsidence as the underlying cause for the local minimum of tropical cyclogenesis in the eastern Caribbean Sea, this present study hopes to shed 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 pre-existing area of divergence. For example, Hurricane Ivan (2004) traversed the region completely unaffected. This further supports the conclusion that subsidence is the primary factor for inhibiting tropical cyclogenesis in this area. If wind shear were a primary factor, one would expect even mature hurricanes to be affected. However, only weaker systems such as weak tropical storms, tropical depressions, and tropical disturbances pose this unique intensity forecasting challenge in the eastern Caribbean. Additionally, the fact that the divergence values in the eastern Caribbean Sea correspond to intensity of the CLLJ on a monthly basis would imply that the divergence maximum in the NCEP Reanalysis is a pre-existing, climatological phenomenon rather than a reflection of the deterioration of convection in that region due to some other unknown factor.

The results of this study suggest that forecasters should take into account the strength of the CLLJ ahead of the tropical disturbance of interest, as the storm enters the eastern Caribbean. Due to the "land-locked" geography of the Caribbean Sea, residents of the surrounding nations depend on accurate forecasts for nascent tropical cyclones in this region.

6. Acknowledgements

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Figure Captions

Fig. 1a – IR satellite image of a tropical disturbance, embedded within the tropical easterlies, just entering the eastern Caribbean at 0015Z on July 16, 2004.

Fig. 1b – IR Satellite image showing a substantial decrease in convection in the tropical disturbance only three hours later.

Fig. 2a – QuikScat monthly average wind data for July 2006. Arrows show only wind direction. Magnitude is depicted by the shades of color. Note the strength of the CLLJ in the central Caribbean.

Fig. 2b – QuikScat monthly average wind data for October 2006. Note the substantially weaker CLLJ in the central Caribbean.

Fig. 3 – Eastern Caribbean domain of study: 12.5° N to 17.5° N and 60° W to 75° W.

Fig. 4 – Horizontal divergence [s^{-1}] climatology at 925 mb for a) June, b) July, c) August, d) September, e) October, and f) November. Note that the divergence values climatologically decrease towards the latter part of the hurricane season, consistent with the variation of the CLLJ.

Fig. 5 – June through November timeseries of eastern Caribbean domain-averaged divergence [s^{-1}] values a) from 1948 to 2004 and b) from 1994 to 2004. Note the cycle of decreasing divergence values throughout each hurricane season.

Fig. 6 – Tropical cyclogenesis frequency distribution of the eastern Caribbean by month from 1851 to 2005. Note the greater relative frequencies towards the latter part of the hurricane season.

Table 1 – Monthly mean 925 mb divergence [s^{-1}] values averaged over the eastern Caribbean domain from 1948 to 2004. Note the decreasing values as the hurricane season progresses.

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

Fig. 1a

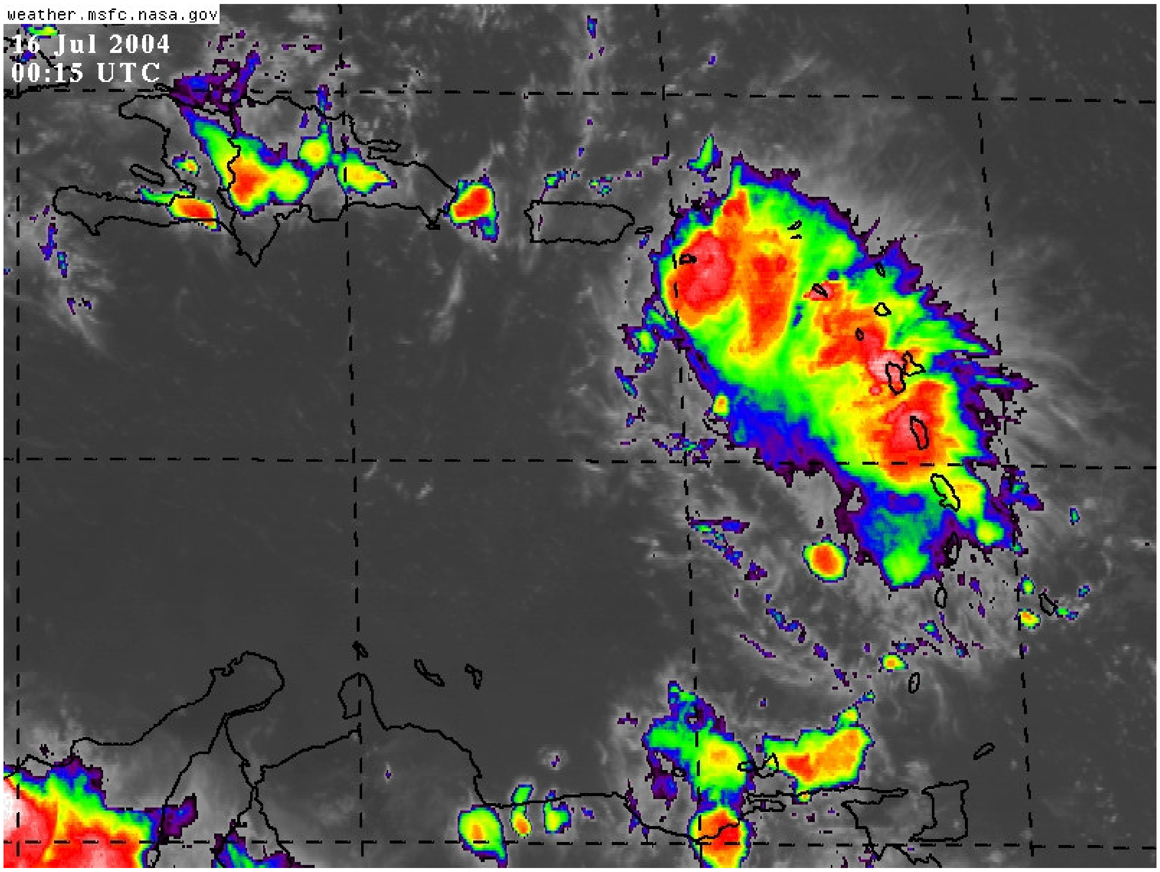


Fig. 1a – IR satellite image of a tropical disturbance, embedded within the tropical easterlies, just entering the eastern Caribbean at 0015Z on July 16, 2004.

Fig. 1b

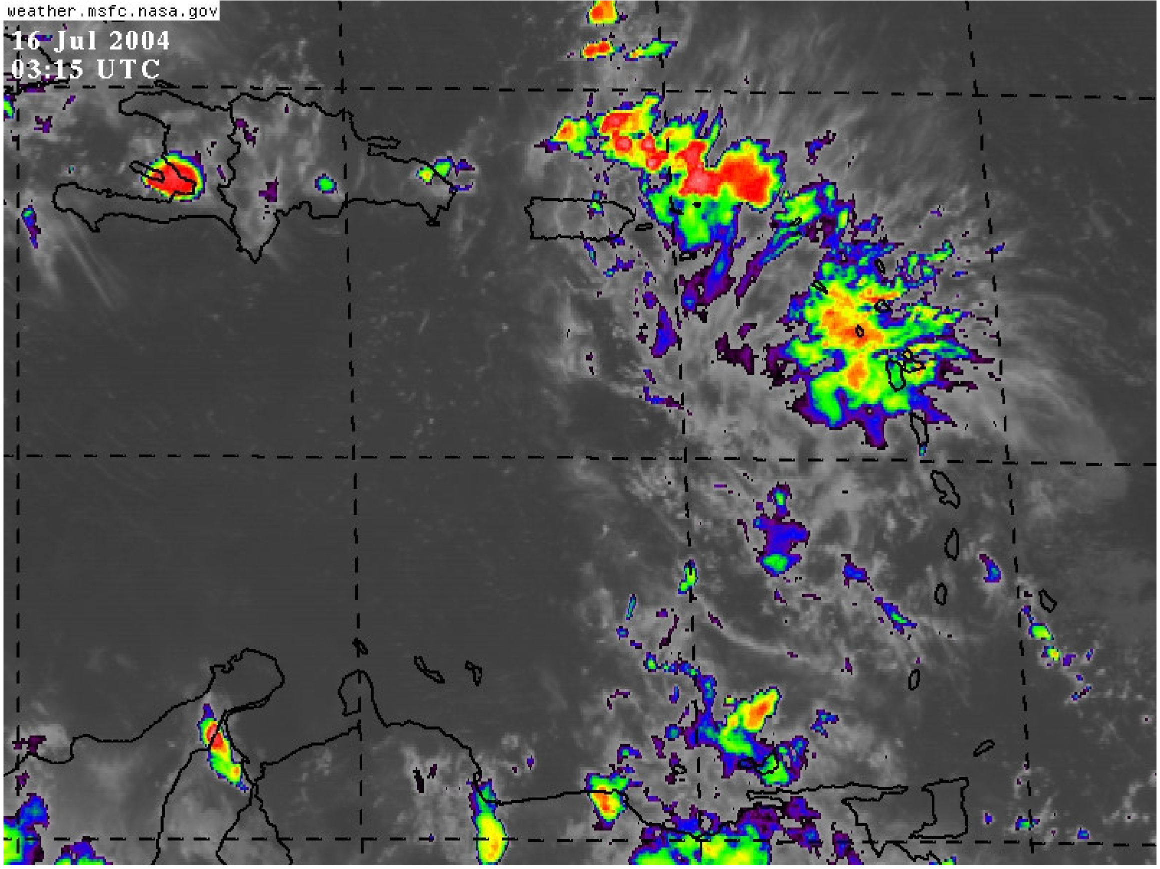


Fig. 1b – IR Satellite image showing a substantial decrease in convection in the tropical disturbance only three hours later.

Fig. 2a

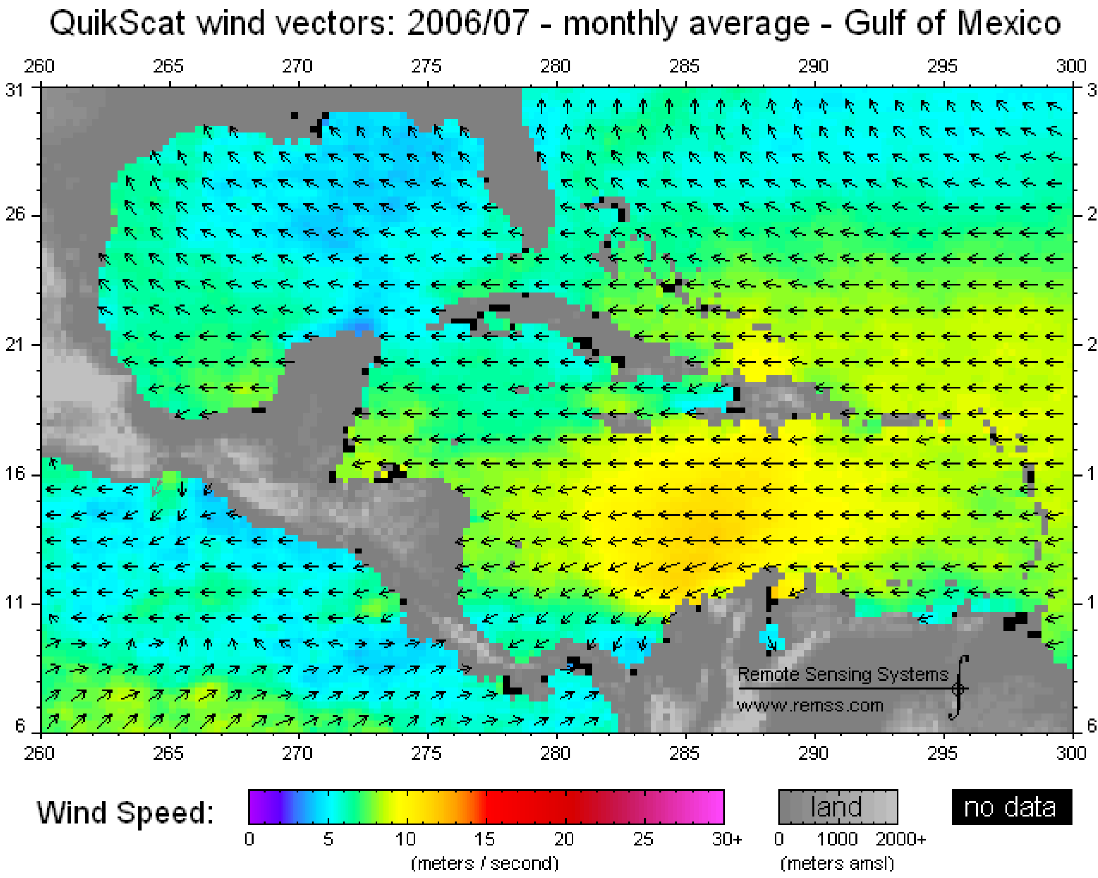


Fig. 2a – QuikScat monthly average wind data for July 2006. Arrows show only wind direction. Magnitude is depicted by the shades of color. Note the strength of the CLLJ in the central Caribbean.

Fig. 2b

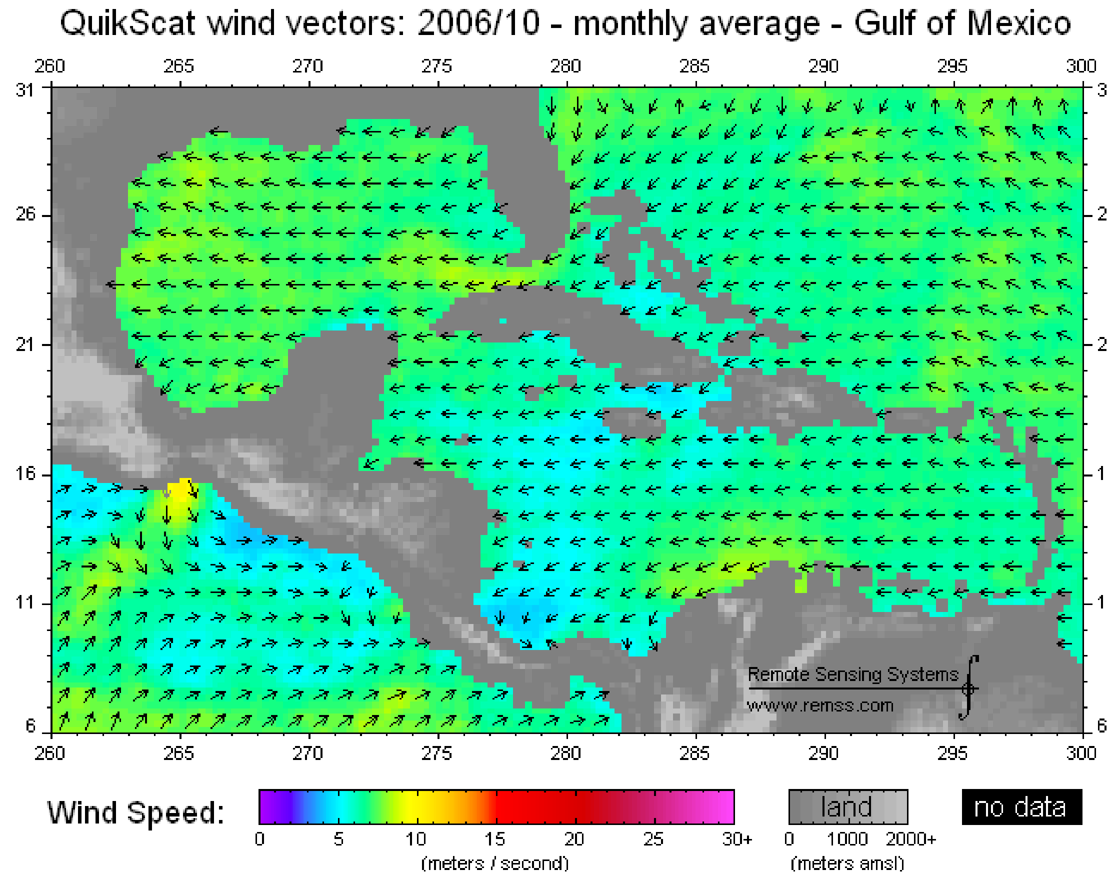


Fig. 2b – QuikScat monthly average wind data for October 2006. Note the substantially weaker CLLJ in the central Caribbean.

Fig. 3

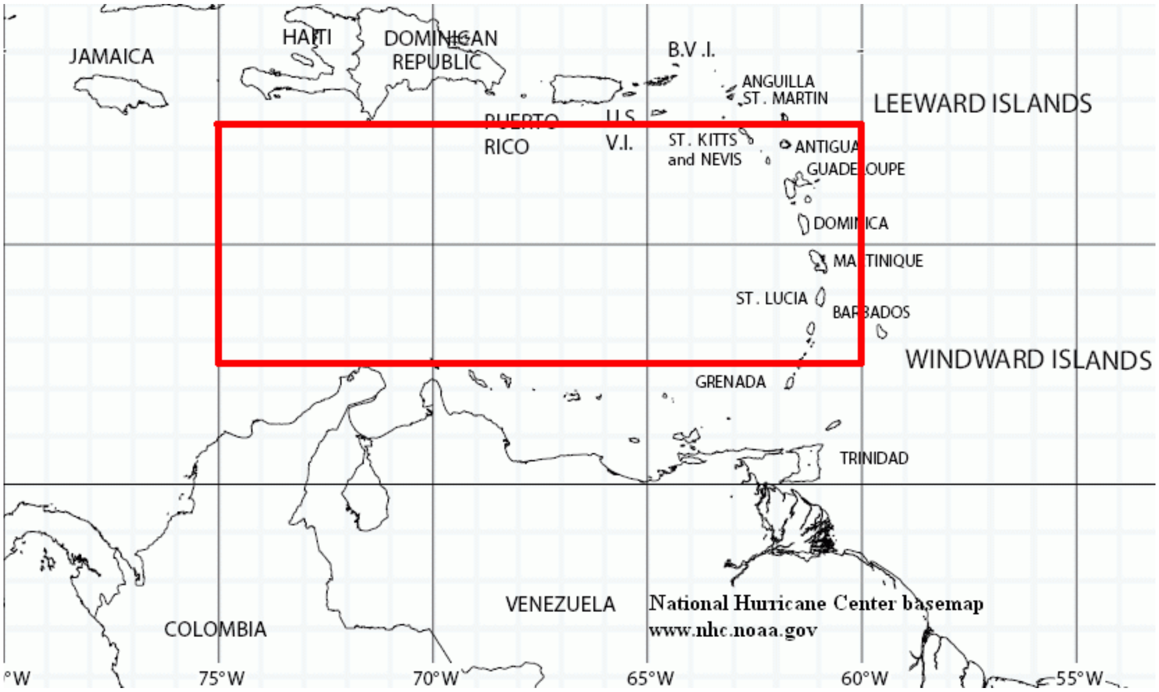
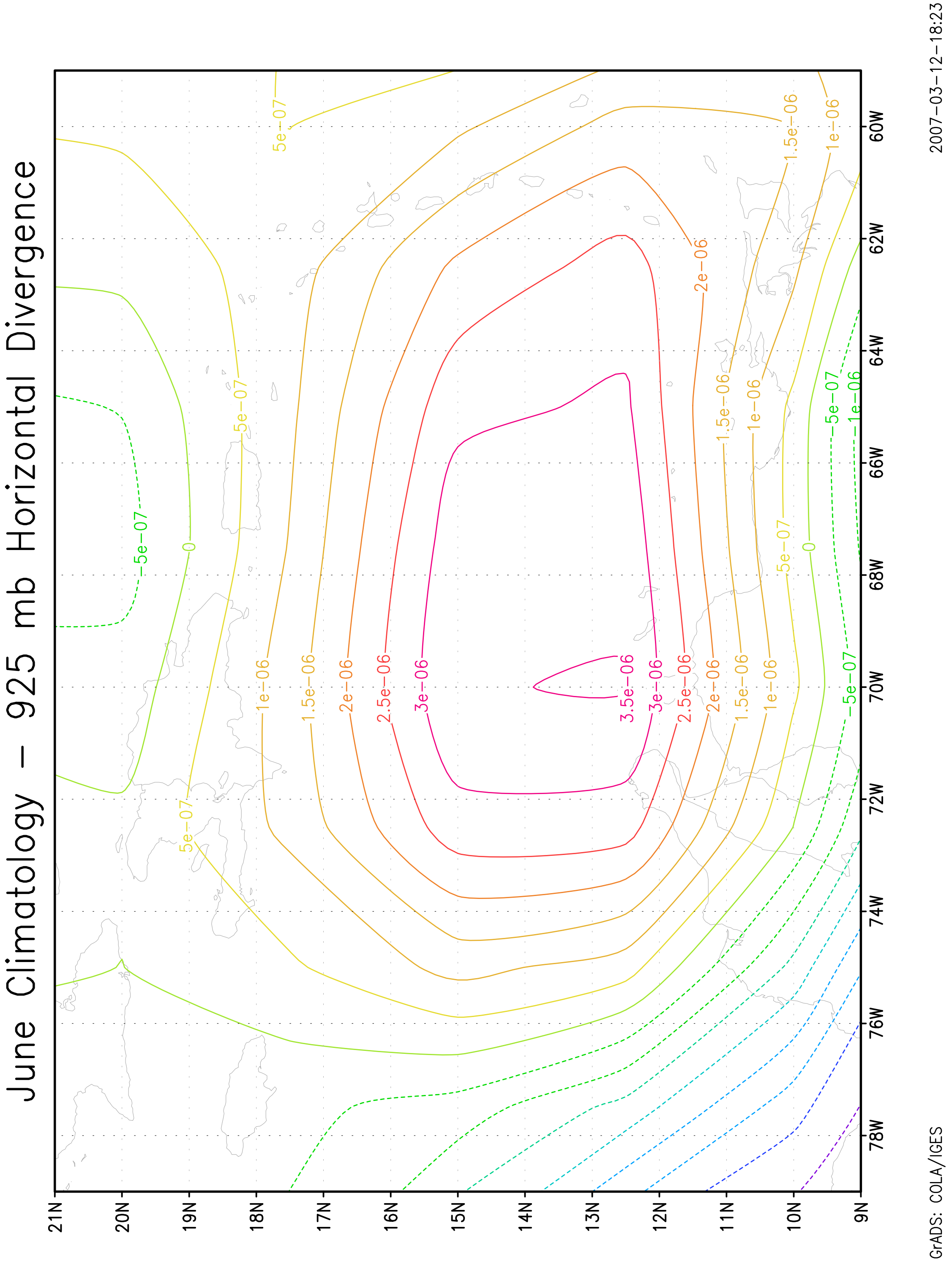


Fig. 3 – Eastern Caribbean domain of study: 12.5° N to 17.5° N and 60° W to 75° W.

Fig. 4a



June Climatology – 925 mb Horizontal Divergence

GrADS: COLA/IGES

2007−03−12−18:23

Fig. 4b

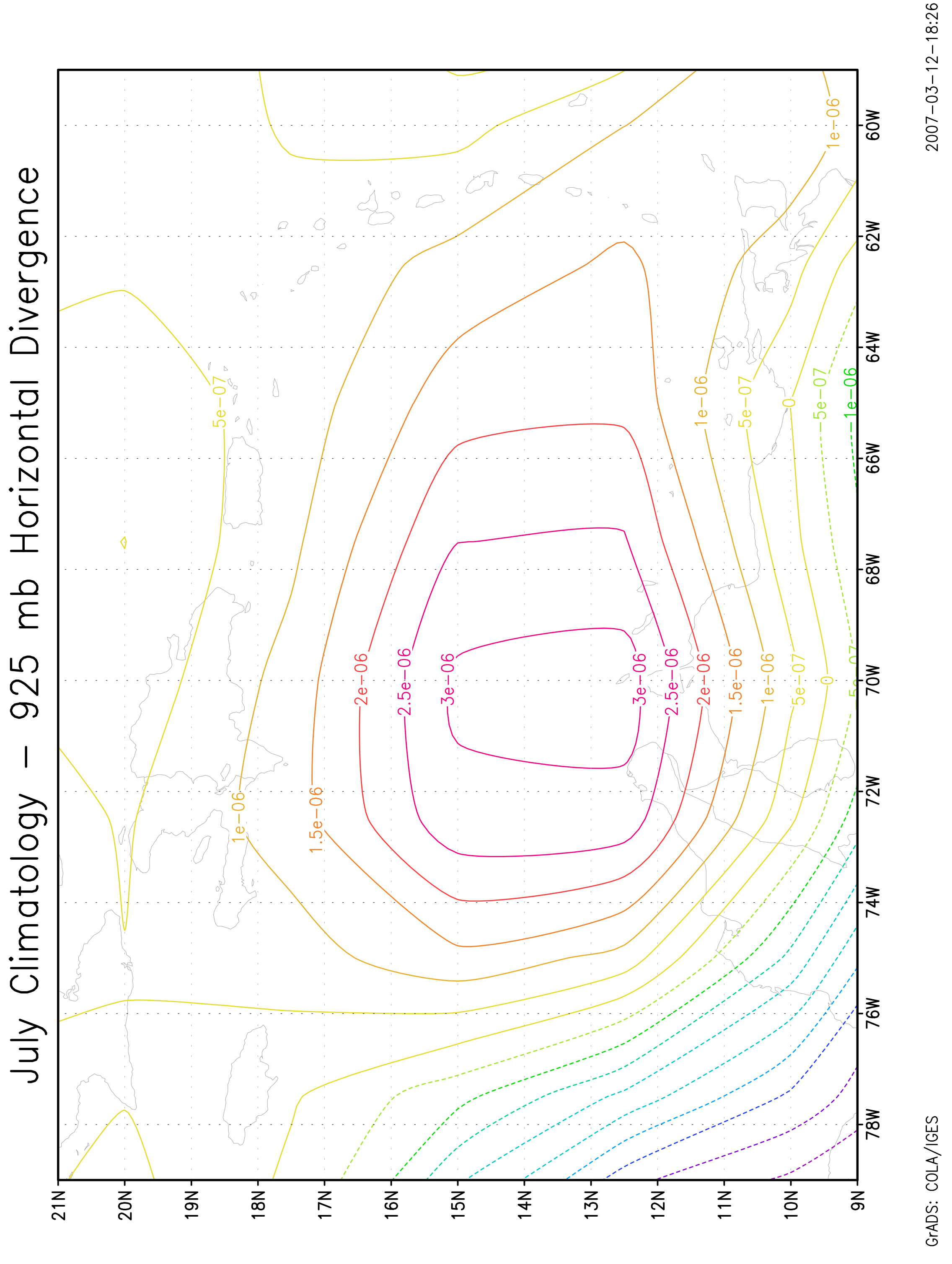

July Climatology – 925 mb Horizontal Divergence
21N
20N
19N
18N
17N
16N
15N
14N
13N
12N
11N
10N
9N
78W
76W
74W
72W
70W
68W
66W
64W
62W
60W
5e-07
1e-06
1.5e-06
2e-06
2.5e-06
3e-06
0
-5e-07
-1e-06
GrADS: COLA/IGES
2007-03-12-18:26

Fig. 4c

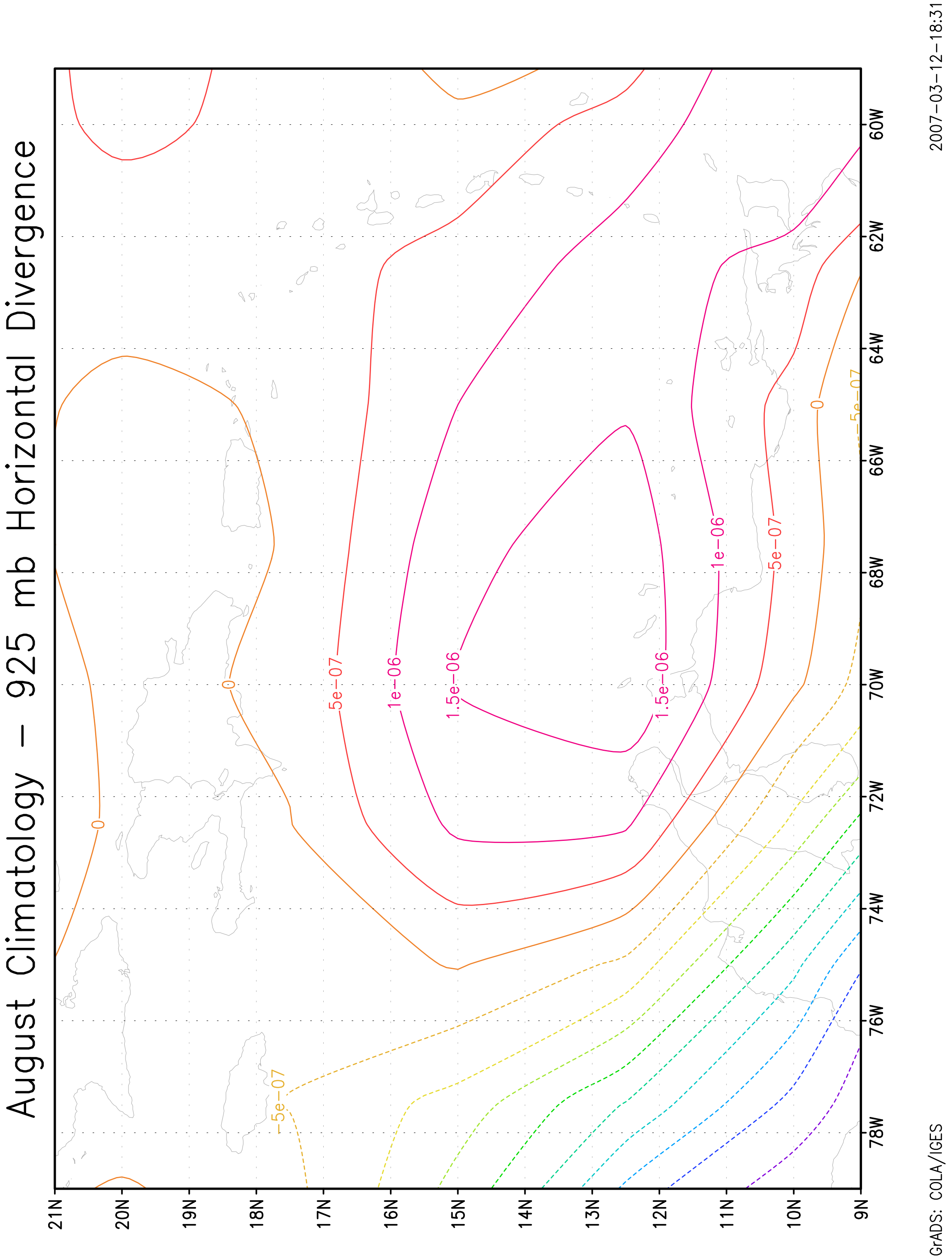

August Climatology - 925 mb Horizontal Divergence
21N
20N
19N
18N
17N
16N
15N
14N
13N
12N
11N
10N
9N
78W
76W
74W
72W
70W
68W
66W
64W
62W
60W
0
-5e-07
5e-07
1e-06
1.5e-06
GrADS: COLA/IGES
2007-03-12-18:31

Fig. 4d

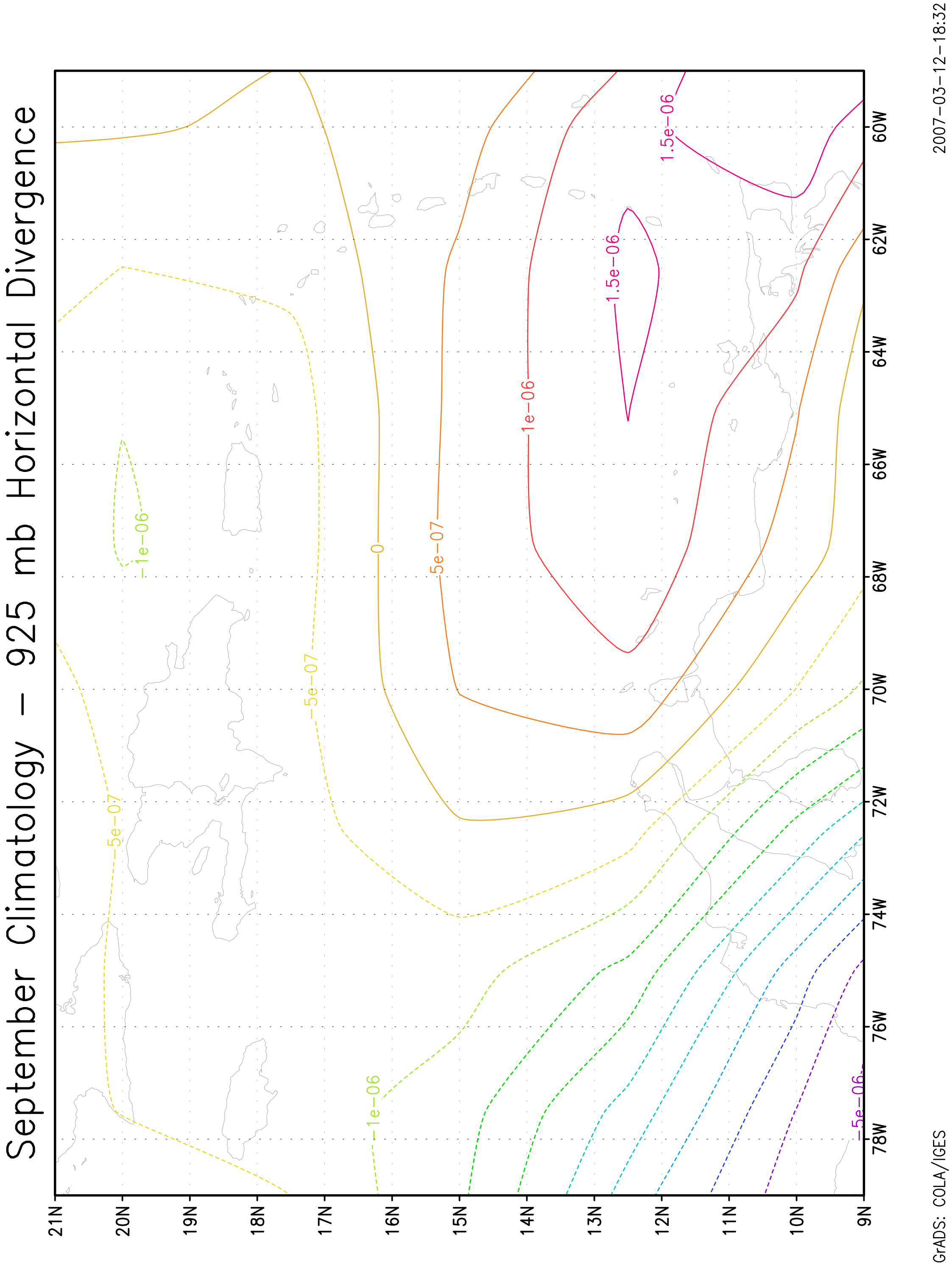

September Climatology – 925 mb Horizontal Divergence
21N
20N
19N
18N
17N
16N
15N
14N
13N
12N
11N
10N
9N
78W
76W
74W
72W
70W
68W
66W
64W
62W
60W
5e-07
-1e-06
-5e-07
0
5e-07
1e-06
1.5e-06
1.5e-06
-1e-06
-5e-06
GrADS: COLA/IGES
2007-03-12-18:32

Fig. 4e

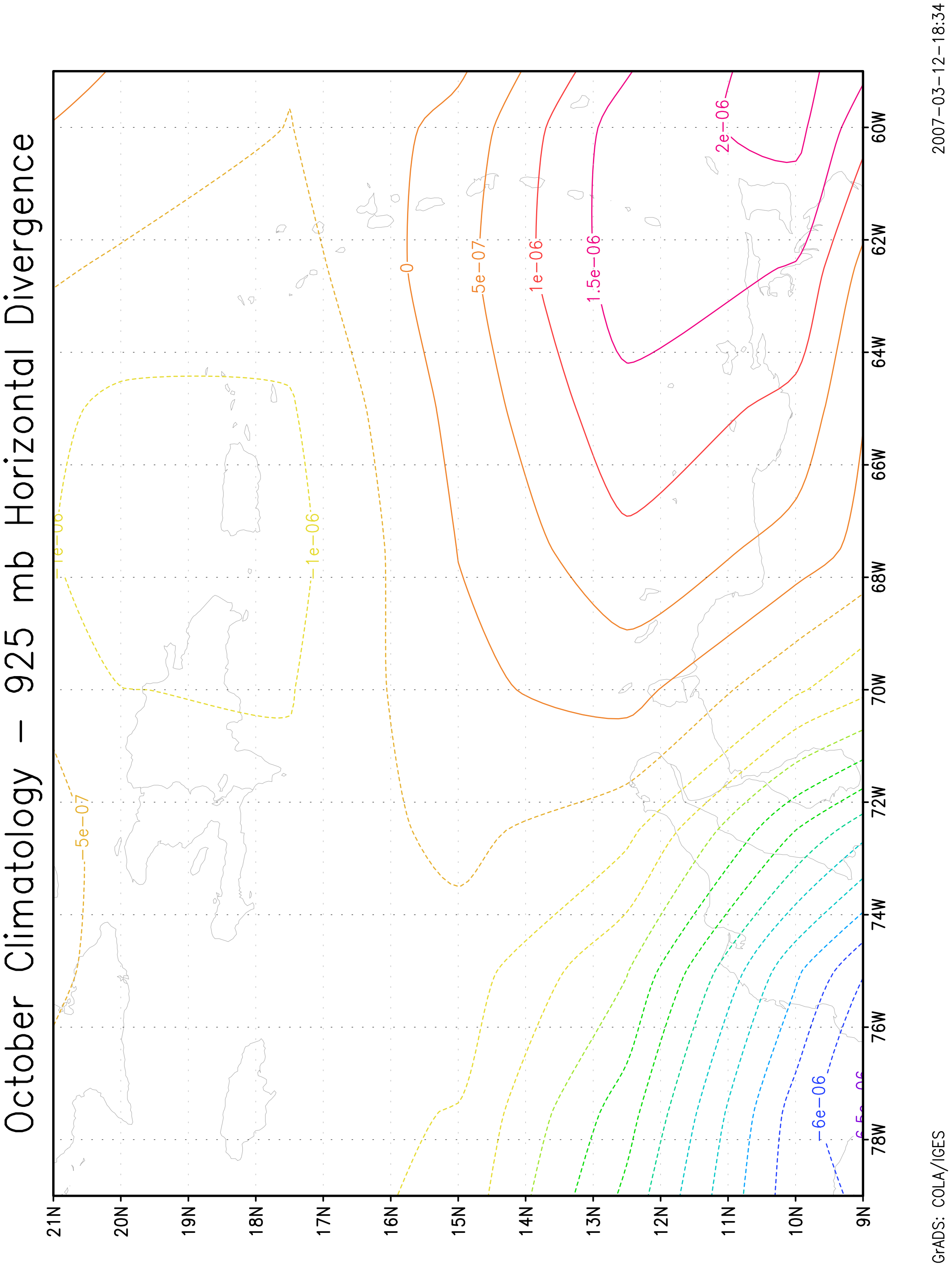
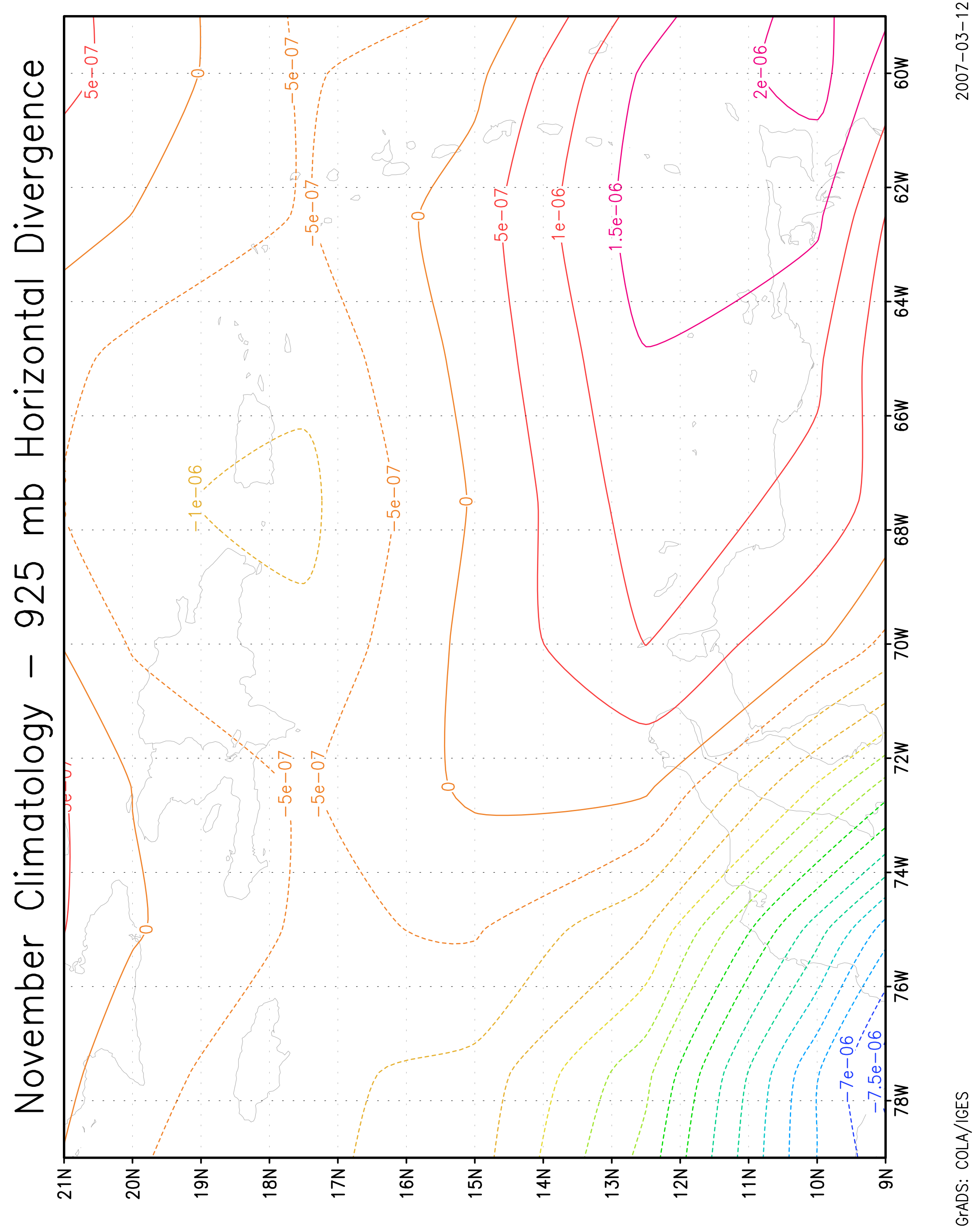

October Climatology – 925 mb Horizontal Divergence
21N
20N
19N
18N
17N
16N
15N
14N
13N
12N
11N
10N
9N
78W
76W
74W
72W
70W
68W
66W
64W
62W
60W
0
5e-07
1e-06
1.5e-06
2e-06
-5e-07
-1e-06
-1e-06
-6e-06
GrADS: COLA/IGES
2007-03-12-18:34

Fig. 4f



GrADS: COLA/IGES

2007-03-12-18:36

Fig. 4 – Horizontal divergence [s^{-1}] climatology at 925 mb for a) June, b) July, c) August, d) September, e) October, and f) November. Note that the divergence values climatologically decrease towards the latter part of the hurricane season, consistent with the variation of the CLLJ.

Table 1

Month	**Mean 925 mb Divergence [s^{-1}]**
June	1.82×10^{-6}
July	1.36×10^{-6}
August	6.46×10^{-7}
September	1.07×10^{-7}
October	-8.59×10^{-8}
November	1.54×10^{-7}

Table 1 – Monthly mean 925 mb divergence [s^{-1}] values averaged over the eastern Caribbean domain from 1948 to 2004. Note the decreasing values as the hurricane season progresses.

Fig. 5a

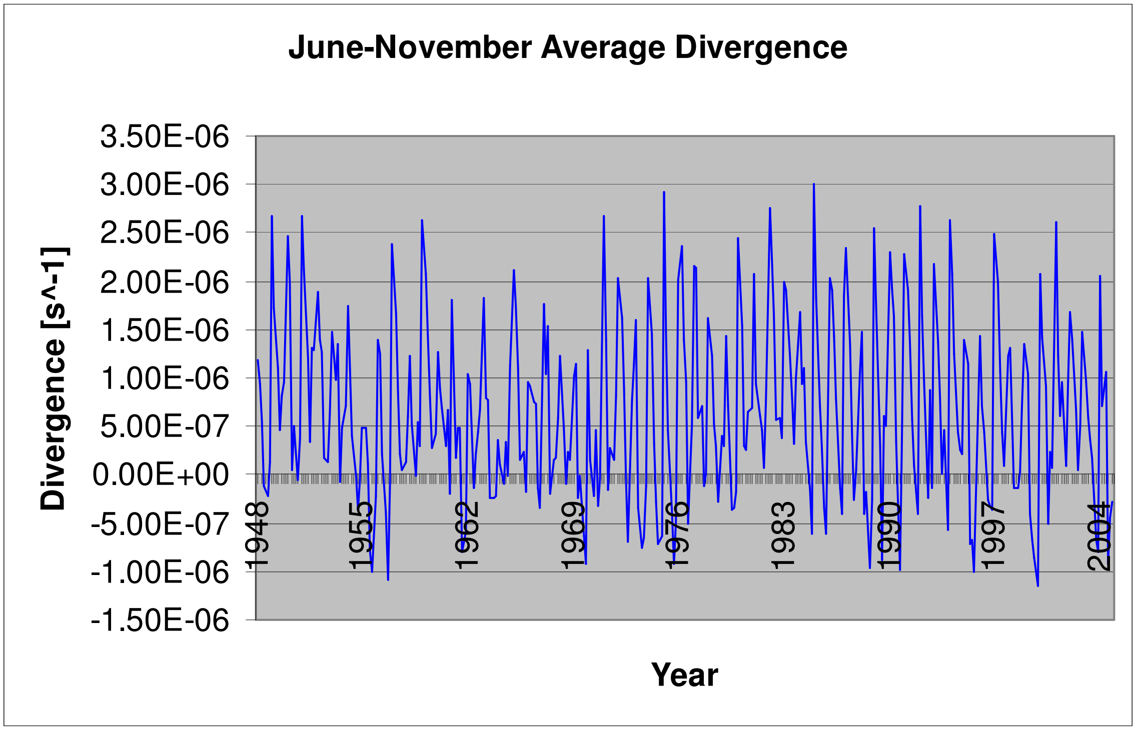

June-November Average Divergence
3.50E-06
3.00E-06
2.50E-06
2.00E-06
1.50E-06
1.00E-06
5.00E-07
0.00E+00
-5.00E-07
-1.00E-06
-1.50E-06
Divergence [s^-1]
1948
1955
1962
1969
1976
1983
1990
1997
2004
Year

Fig. 5b

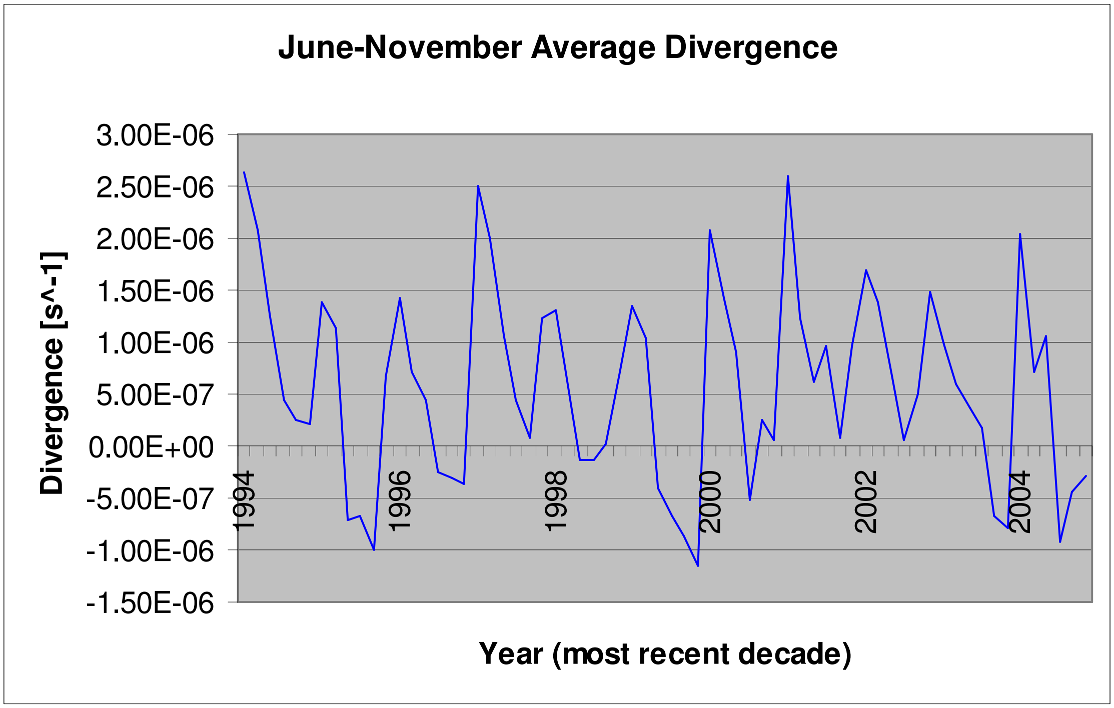

June-November Average Divergence
3.00E-06
2.50E-06
2.00E-06
1.50E-06
1.00E-06
5.00E-07
0.00E+00
-5.00E-07
-1.00E-06
-1.50E-06
Divergence [s^-1]
1994
1996
1998
2000
2002
2004
Year (most recent decade)

Fig. 5 – June through November time series of eastern Caribbean domain-averaged divergence [s^{-1}] values a) from 1948 to 2004 and b) from 1994 to 2004. Note the cycle of decreasing divergence values throughout each hurricane season. Only the data points for June through November are included.

Fig. 6

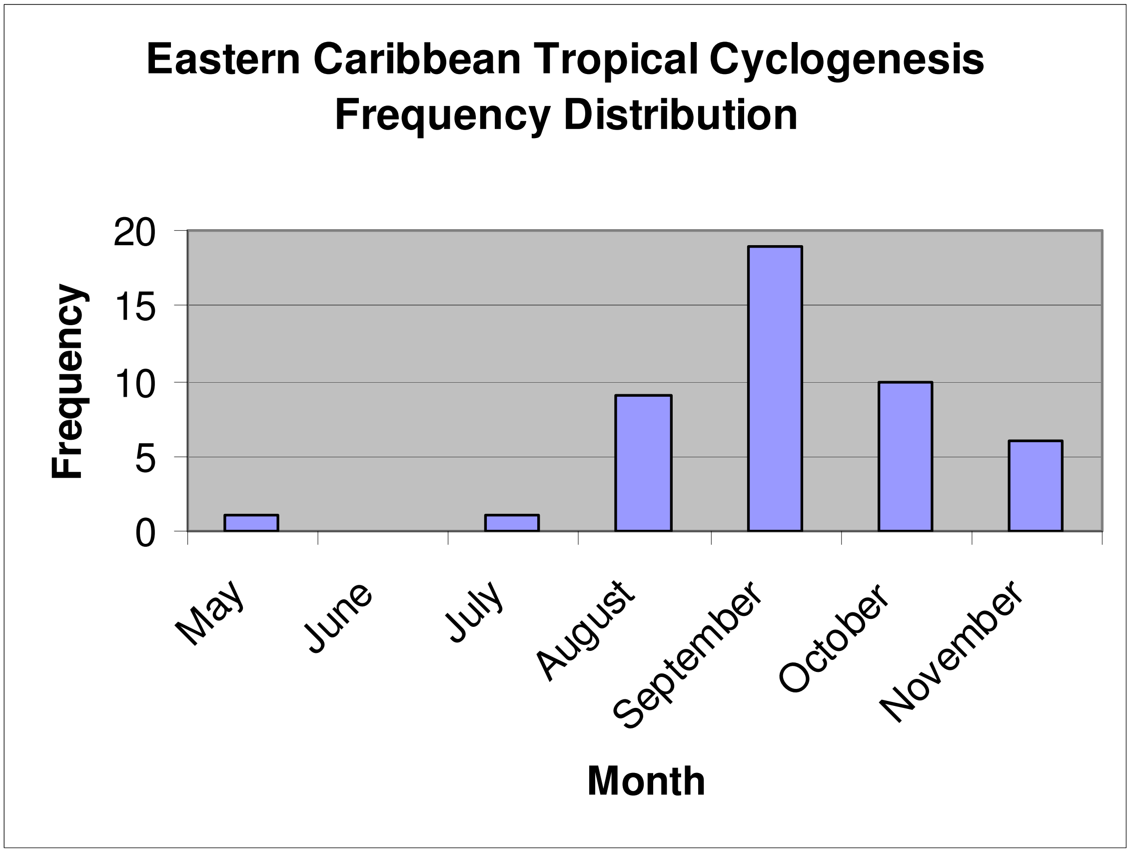


Fig. 6 – Tropical cyclogenesis frequency distribution of the eastern Caribbean by month from 1851 to 2005. Note the greater relative frequencies towards the latter part of the hurricane season.

Table 2

Month	0-lag Correlation Coefficient (r) Monthly Divergence vs. SOI
June	-0.39
July	-0.46
August	-0.61
September	-0.36
October	-0.39
November	-0.13

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