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The Rapid Intensification of Hurricane Gustav (2008)

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Abstract

Hurricane Gustav was one of two major hurricanes that occurred in the Atlantic basin during the 2008 hurricane season. The storm caused more than $6 billion U. S. dollars of damage in Haiti, Jamaica, Cuba, and along the coast of the Gulf of Mexico from 25 August 2008 to 5 September 2008. The greatest amount of damage and highest number of casualties produced by the storm can be attributed to the rapid intensification of the hurricane. Rapid intensification (RI) of a tropical cyclone is defined as an increase in maximum sustained winds by 15.4 m s^{-1} (30 kts) in a continuous 24 h period. Between 1200 UTC 29 August and 2200 UTC 30 August, the minimum pressure of Gustav decreased by 48 hPa and the maximum sustained winds increased by 80 kts from a tropical storm to a category four hurricane on the Saffir-Simpson scale. This increase in intensity exceeds the definition of RI.

Traditionally, the parameters of ocean heat content, vertical wind shear, and atmospheric moisture content have been evaluated to assess changes in tropical cyclone intensity. Kaplan and DeMaria (2003) have shown that sea surface temperatures (SSTs) in excess of 28.4°C and low vertical wind shear values (approximately 5 m s^{-1}) are conducive for RI. A moist atmosphere (i.e., high values of relative humidity) also signals an atmospheric environment conducive to tropical cyclone intensification. The SST field from the National Oceanic and Atmospheric Administration Optimum Interpolation 1/4° Daily SST Analysis (NOAA-OISST) dataset was used to assess the ocean heat content in the vicinity of the storm during its lifespan. Data from the initialization of the Global Forecasting System (GFS) was used to evaluate 200-850 hPa vertical wind shear, 850-700 hPa layer averaged relative humidity, and 200 hPa divergence. Lightning flash data from the World Wide Lightning Location Network (WWLLN) is used to investigate the role of convection in the RI of the storm.

The SST and atmospheric relative humidity fields in the vicinity of Hurricane Gustav were conducive to the storm's intensification, but values of vertical wind shear in the vicinity of the storm were greater than 10 m s^{-1}, a magnitude typical of tropical cyclone weakening. A convective band formed 12 h prior to the onset of the storm's RI, which led to the broadening of a 200-hPa divergent area in the vicinity of the storm. It is hypothesized that the broadening of this area allowed for a positive feedback loop that allowed for the RI of the storm.

1. Introduction

Kaplan and DeMaria (2003) defined the rapid intensification (RI) of a tropical cyclone as an increase in maximum sustained winds of at least 15.4 m s^{-1} (30 kt) in a 24-h period. In that same study, several parameters were established in order to predict RI events. Of particular interest, values of sea surface temperature, vertical wind shear, lower-level relative humidity, and upper-tropospheric wind 200-800-km from the center of the storm prior to RI events were statistically significantly different than values of those parameters for non-RI events. Kaplan et al. (2010) added ocean heat content and upper-tropospheric divergence as parameters that have statistically significantly different values for RI versus non-RI events.

Hurricane Gustav was the first of two major hurricanes that impacted the western Caribbean and Gulf Coast regions in 2008. Figure 1 (Figure 1 from Beven and Kimberlain (2009)) shows the best track of Gustav from the National Hurricane Center. Gustav formed as Tropical Depression Seven on 25 August 2008 in the northeastern Caribbean Sea. Over the next ten days, Hurricane Gustav caused over $6.6 billion U.S. dollars worth of damage and over 150 casualties in Hispanola, Jamaica, Cuba, and along the northern Gulf Coast and regions inland, particularly in Louisiana, Mississippi, and Arkansas. The peak of the storm's intensity occurred shortly before its landfall in Cuba as a category 4 hurricane on the Saffir-Simpson scale during the morning of 30

August. This peak occurred after a period of rapid intensification, as the storm was only at tropical storm strength 24 h earlier. Hurricane Gustav entered the Gulf of Mexico later in the day and weakened to below major hurricane status. On 1 September, Hurricane Gustav made landfall in central Louisiana. Impacts in the northern Gulf Coast region included intense wind damage in Baton Rouge, Louisiana; flooding in many areas in Louisiana along the Mississippi River; and disruption of oil production in the region. Gustav underwent extratropical transition over the next few days before being absorbed by a midlatitude low on 5 September.

Figure 2 (Figure 2 from Beven and Kimberlain (2009)) shows a time series of the maximum sustained winds of Gustav from the National Hurricane Center. From 1200 UTC 29 August to 2200 UTC 30 August, Gustav rapidly intensified from a tropical storm, with a minimum pressure of 989 hPa and 25.72 m s^{-1} (50 kt) maximum sustained winds, to its peak intensity as a category 4 hurricane, with a minimum pressure of 941 hPa and 69.45 m s^{-1} (135 kt) maximum sustained winds. During this period, Gustav moved from the western tip of Jamaica to Isla de la Juventud and the western extremities of Cuba. The first stage of this study examines the synoptic-scale environment surrounding Gustav, particularly the area where Gustav tracked during RI. During this stage, synoptic variables established by Kaplan and DeMaria (2003) and Kaplan et al. (2010) are evaluated.

The second stage of this study evaluates the convective structure of Gustav prior to the onset of RI. To perform this analysis, lightning flashes are used as a proxy for convection. Abarca et al. (2011) analyzed convective activity in tropical cyclones using flashes from the World Wide Lightning Location Network (WWLLN). Their findings suggest that flash density in the inner core could be used as a parameter for distinguishing intensifiying from non-intensifying tropical cyclones, especially in tropical depressions and tropical storms. Solorzano et al. (2008) also noted eyewall lightning outbreaks in several Atlantic and Western Pacific basin tropical cyclones prior to eyewall replacement cycles using WWLLN flash data. They also noted that flash density during

lightning outbreaks are maximized in the eyewall and rainband regions, and that eyewall lightning outbreaks occur prior to and during major intensity changes. This agrees with Squires and Businger (2008), who found eyewall lightning outbreaks prior to the onset of RI, at the end of RI, and during the maximum intensity of Hurricanes Katrina and Rita (2005) using Long-Range Lightning Detection Network flash data.

Several studies have examined tropical cyclone intensification events in areas with high values of vertical shear. Hanley et al. (2001) suggest that RI events are less likely to occur in environments with forcing from upper level troughs and cold lows, which are environments that typically exhibit large values of wind shear, than in environments without those influences. In contrast, Molinari et al. (2004) examined the intensification of Hurricane Danny (1997) and Molinari and Vollaro (2004) the rapid intensification of Tropical Storm Gabrielle (2001) in sheared environments. These studies have employed mesoscale analyses using data from the National Lightning Detection Network (NLDN) and Weather Surveillance Radar-1988 Doppler (WSR-88D) data, respectively. Due to the spatial domains of the NLDN and WSR-88D not extending to the area where Gustav rapidly intensified, WWLLN data is seen as a desired choice for the mesoscale analysis of Gustav.

2. Data and methodology

This study consists of two parts: a synoptic-scale analysis and a mesoscale analysis. The first part analyzes several synoptic-scale parameters outlined by Kaplan and DeMaria (2003) and Kaplan et al. (2010) as conducive for RI events. The sea surface temperature (SST) distribution at the onset of RI is analyzed from the National Oceanic and Atmospheric Administration Optimum Interpolation 1/4° Daily Sea Surface Temperature Analysis (NOAA OISST) dataset. Since the data in this dataset contains daily average SST data, the data for 29 August 2008 is analyzed as the SST

distribution at the onset of RI, despite being labeled as for 0000 UTC 29 August 2008. This data was plotted using Integrated Data Viewer (IDV). The remaining synoptic-scale parameters analyzed in this study are 200-hPa geopotential height and divergence, 200–850-hPa vertical wind shear, and 850–700-hPa layer averaged relative humidity. Data from the initialization from the 1° Global Forecasting System is sued to analyze these parameters. This data was plotted in GEMPAK at the onset of RI, 1200 UTC 29 September.

The second part of this study analyzes the convective structure of Gustav prior to the onset of RI. Lightning flash data from the World Wide Lightning Location Network is selected for analysis due to its availability in relation to the location of Gustav's RI. This data was plotted using SigmaPlot and the National Center for Atmospheric Research (NCAR) Command Language (NCL).

3. Results

a. Synoptic-scale analysis

Figure 3 shows the daily averaged sea surface temperature for the Caribbean and Western Atlantic basin for 29 August 2008. At the onset of RI, sea surface temperatures to the northwest of Gustav are predominantly greater than 29°C. During RI, Gustav interacts with this area as it progresses northwestward. The interaction with this area agrees with the mean value of 28.4°C as a parameter for RI as determined by Kaplan and DeMaria (2003). Additionally, the high sea surface temperatures signal sufficient oceanic energy required for RI.

Figure 4 shows the 850–700-hPa layer averaged relative humidity for the Caribbean and Western Atlantic basin for 1200 UTC 29 August 2008. At the onset of RI, a broad area of lower-level relative humidity values of greater than 70% dominates the basin. It is noteworthy that over the western areas of Cuba there is a dry area, with a relative humidity minimum of less than 50%. The

relative humidity values in this area suggest an environment that is not conducive for RI. The moist area to the south and east of the storm offsets the dry area to the northwest and allows for the sufficient moisture that is necessary for RI. In addition, this area allows for the mean value lower-level relative humidity at the onset of RI to be comparable with the mean of 69.7% established by Kaplan and DeMaria (2003).

Figure 5 shows the 200-hPa divergence for the Caribbean and Western Atlantic basin at 1200 UTC 29 August 2008. At the onset of RI, a broad area of divergence is present to the southeast of the center of the storm. Comparison to the mean value established by Kaplan et al. (2010) of 4.69×10^{-6} s^{-1} (written as 46.9×10^{-7} s^{-1} in their paper) is more difficult to analyze due to differences in the usual scaling of divergence, which is typically 10^{-5} s^{-1}. Further analysis of divergence is given in Section 3b. It is hypothesized that this broad area of divergence southeast of the center of Gustav is sufficient for RI.

Figure 5 also shows the 200-hPa geopotential heights over the Caribbean and Western Atlantic basin for 1200 UTC 29 August 2008. Although not a variable that is discussed by Kaplan and DeMaria (2003) or Kaplan et al. (2010), it is noteworthy that there is an upper-level trough to the northwest of Gustav at the onset of RI. This contradicts Hanley et al. (2001), who suggested that interaction with a synoptic-scale upper-level trough is not favorable for tropical cyclone development. Further, this particular trough contributes significantly to the presence of high values of vertical wind shear, as seen in Figure 6, the 850–200 hPa wind shear at 1200 UTC 29 August 2008. To the northwest of Gustav, a broad area with magnitudes of vertical wind shear greater than 10 m s^{-1} (greater than 15 m s^{-1} over much of Cuba) is present. This disagrees with the mean parameter of 4.8 m s^{-1} of 850–200-hPa wind shear as established by Kaplan and DeMaria (2003). Furthermore, this shear originates from predominantly westerly 200-hPa winds, which is shown to be less favorable for RI than easterly 200-hPa winds (Kaplan and DeMaria 2003).

To summarize the synoptic-scale analysis, several of the parameters established by Kaplan and DeMaria (2003) and Kaplan et al. (2010) were conducive in RI in Gustav's environment. Those parameters were sea surface temperature, 850–700-hPa relative humidity, and 200-hPa divergence. However, 850–200-hPa wind shear in the vicinity of Gustav at the onset of RI was not conducive to RI. This leads to the necessity of analysis beyond the synoptic scale, which is discussed in the next section.

b. Mesoscale analysis

Figure 7 is a Hovmöller diagram of World Wide Lightning Location Network (WWLLN) flash densities from 0000 UTC 25 August to 0000 UTC 2 September 2008. The x-axis of the diagram represents time, increasing to the right. The y-axis of the diagram represents a 20-km radial bin, increasing with distance from the center of the storm progressing toward the top of the diagram. Three notable distinct outbreaks of flashes are present. The first involves an area of flashes progressing outward from the center of the storm from 1800 UTC 26 August to 0000 UTC 28 August. This period of convective activity is associated with the storm's interaction with Hispaniola and weakening following its first landfall. The second outbreak involves flashes that develop, with a density maximum occurring approximately 300 km from the center of the storm, within 12 h prior to the onset of RI. This activity is highlighted by a green ellipse on Figure 7. The third outbreak occurs greater than 300 km from the center of the storm from 1200 UTC 30 August to 0600 UTC 31 August. This final outbreak occurs near the end of the RI period. A common theme with all three outbreaks is that they occur prior to major changes in storm intensity. This theme is consistent with the findings of several studies (Solorzano et al. 2008; Squires and Businger 2008).

Further interest is taken into the second lightning outbreak. Figures 8a, b, and c show lightning flashes near the center of Gustav from 2330 UTC 28 August to 0029 UTC 29 August

(hereafter the 0000 UTC 29 August profile), from 0530 UTC to 0629 UTC 29 August (hereafter the 0600 UTC 29 August profile), and from 1130 UTC to 1229 UTC 29 August (hereafter the 1200 UTC 29 August profile), respectively. The blue ellipses in each figure denote an area of focus associated with the second outbreak. At the beginning (0000 UTC; Figure 8a) and end (1200 UTC; Figure 8c) of the outbreak, very few flashes occur within the ellipse. In contrast, the bulk of the flashes of the outbreak occur at 0600 UTC (Figure 8b) in a single convective band southeast of the center of the storm.

Figures 9a and b are the same as Figure 5, except for 0000 UTC and 1200 UTC 29 August 2008, respectively. In addition, Figures 9a and b contain dark blue ellipses denoting the area of convective activity associated with the second major lightning outbreak. Throughout the period of the outbreak, an area of upper-level divergence is present to the southeast of the center of the storm. It is noteworthy to mention that a bull's-eye of divergence occurs within the ellipse at the beginning of the outbreak, but is located to the east of the ellipse at the end of the outbreak. It is most interesting that the $6 \times 10^{-5} \text{ s}^{-1}$ contour at the latter time encompasses a greater area than the former time. In addition, the broad area of divergence as a whole encompasses a greater area at 1200 UTC than 0000 UTC. This phenomenon is interpreted as the broadening of the divergent area due to convective activity associated with the lightning flashes that occurred during the outbreak.

4. Discussion

The role of divergence in the rapid intensification of TC Gustav can be debated. One idea suggests that the increase in divergence is simply the product of the developing upper-level anticyclone that is expected with tropical cyclone development. However, Gustav actually weakened during the second major lightning outbreak as it interacted with Jamaica following its second landfall. The analysis of the broadening of the divergent area was therefore attributed to

the convective activity that occurred during the outbreak. It must also be noted that the synoptic-scale statistics of Kaplan et al. (2010) did indicate that the mean value of 200-hPa divergence is statistically significantly higher for RI events than for non-RI events. This supports an alternative idea that the broadening divergent area played a role in Gustav's RI.

A hypothesis is offered for the physical interpretation of the role of an increasingly divergent area in Gustav's RI. The broadening area of increased divergence allows for increased vertical motion under the divergent area. The increased vertical motion allows for enhanced diabatic heating from condensation of rising air parcels. Through hydrostatic adjustment, the enhanced diabatic heating expands the decreases the central pressure of the storm. The pressure gradient surrounding the center of the storm then increases in magnitude. The increased pressure gradient allows for the magnitude of the lower-level winds surrounding the storm to increase. The enhanced lower-level winds cause an enhanced wind-induced surface heat exchange (WISHE; Emanuel 1986) process, which creates a positive feedback loop through increased surface fluxes of heat and moisture at the ocean surface, increased convection and increased diabatic heating. It is hypothesized that Gustav's RI can be attributed to a positive feedback loop involving an enhanced WISHE process, which is triggered by an increase in upper-level divergence.

5. Summary

Analyses on the synoptic scale and the mesoscale were performed to understand the rapid intensification of Tropical Cyclone Gustav. On the synoptic-scale, it was shown that several parameters established by previous studies (Kaplan and DeMaria 2003; Kaplan et al. 2010) signaled conditions conducive to RI. Those parameters were sea surface temperature, 850–700-hPa relative humidity, and 200-hPa divergence. It was also shown that a 200-hPa geopotential height trough allowed for values of 850–200-hPa wind shear that were unfavorable for RI. On the

mesoscale, a convective band was shown to have formed within 12 h of onset of Gustav's RI. It was also shown that an area of 200-hPa divergence in the vicinity of Gustav had broadened and increased in magnitude. Finally, a hypothesis was offered connecting the increased divergence to Gustav's RI through a positive feedback loop involving the WISHE process.

Acknowledgments

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Squires, K., and S. Businger, 2008: The morphology of eyewall lightning oubreaks in two category 5
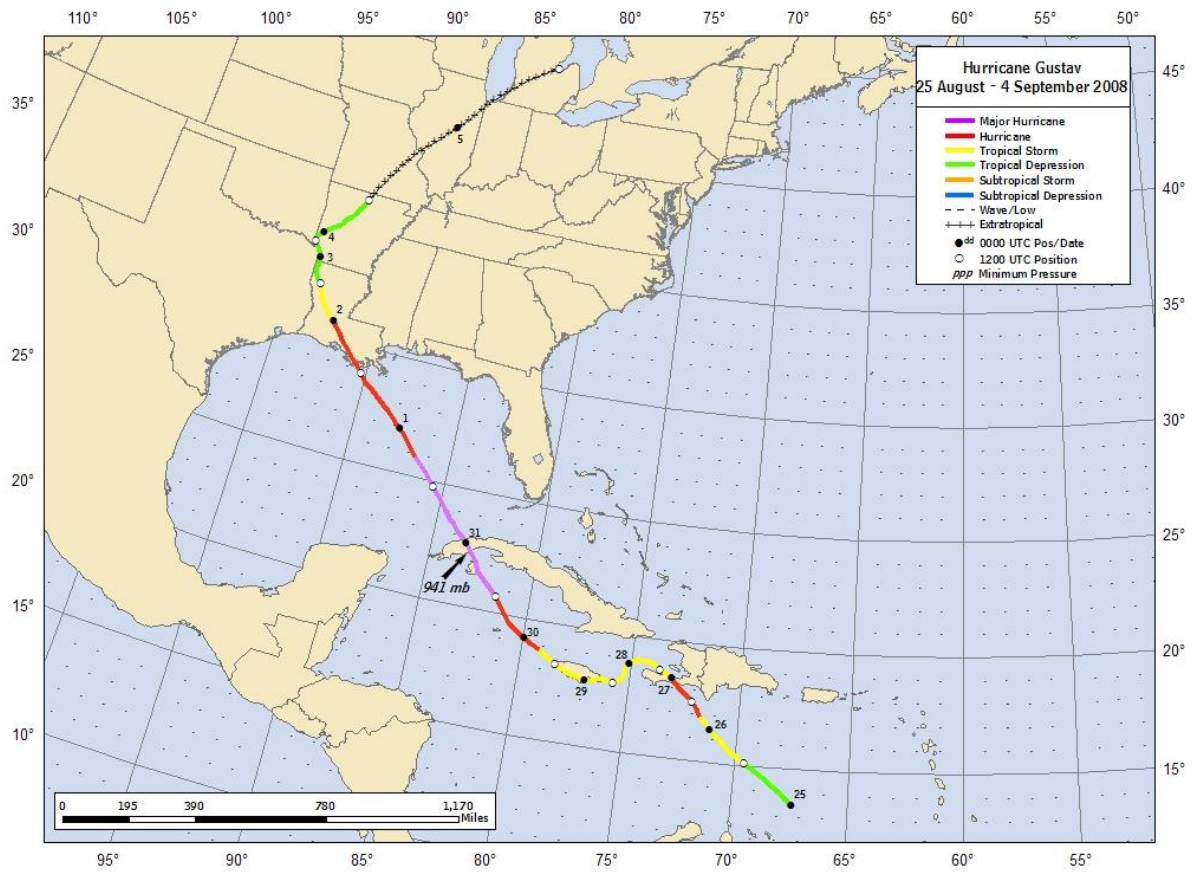hurricanes. *Mon. Wea. Rev.,* **136,** 1706-1726.

Figure 1. Best track positions for Tropical Cyclone (TC) Gustav from 25 August to 4 September

2008 from the National Hurricane Center. Track during the extratropical stage is based on analyses

from the National Oceanic and Atmospheric Administration (NOAA) Hydrometeorological

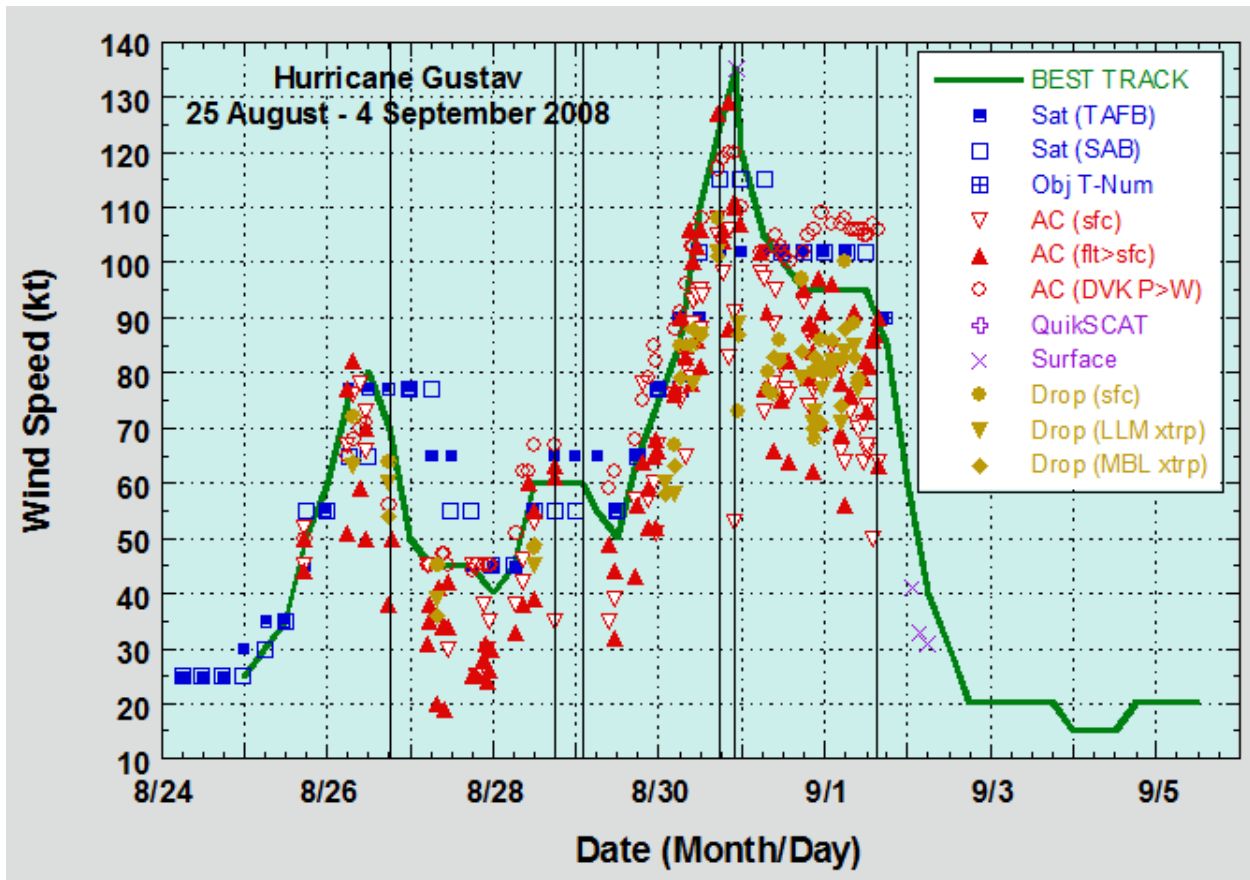Prediction Center. (Figure 1 of Beven and Kimberlain (2009))

Figure 2. Maximum sustained wind speeds for TC Gustav from 24 August to 5 September 2008

from the National Hurricane Center. (Figure 2 from Beven and Kimberlain (2009))
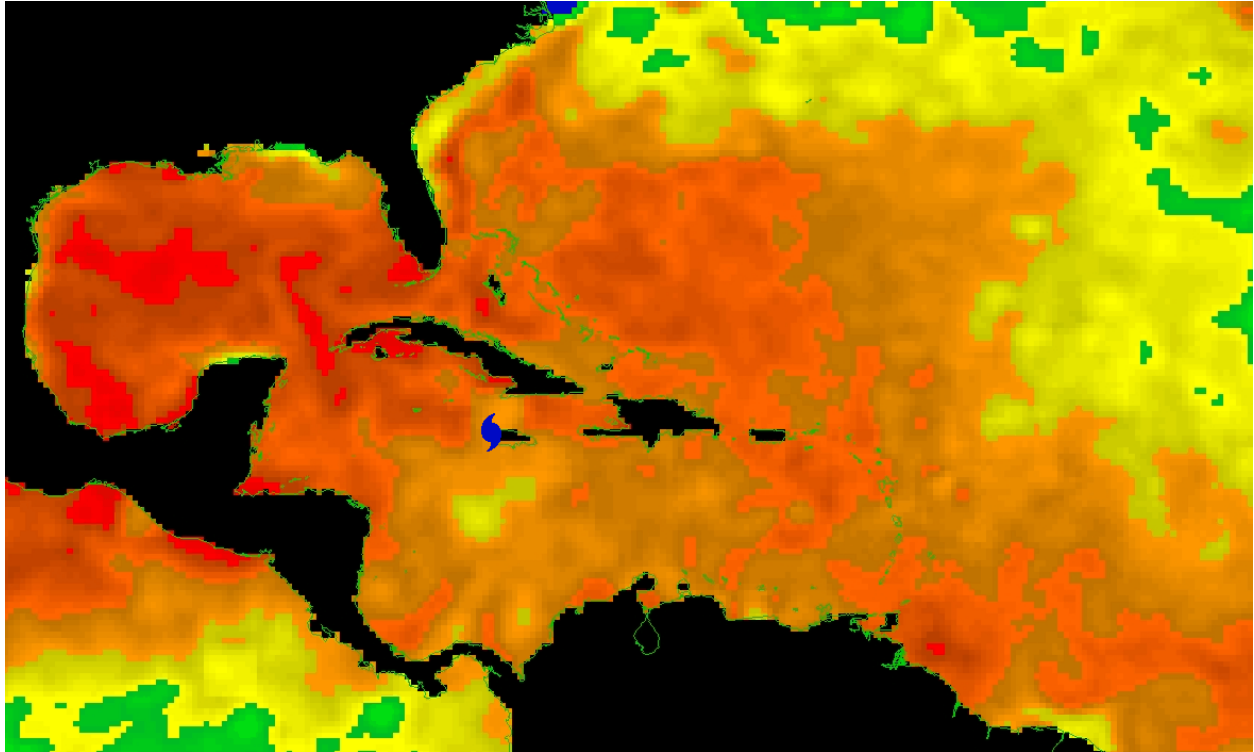
Figure 3. Sea surface temperature (SST) distribution for 29 August 2008. Areas in green represent SSTs of greater than 26°C. Areas in yellow represent SSTs of greater than 27°C. Areas in yellow-orange represent SSTs of greater than 28°C. Areas in red-orange represent SSTs of greater than 29°C. Areas in red represent SSTs of greater than 30°C. Blue hurricane symbol represents the central location of Gustav at 1200 UTC 29 August.
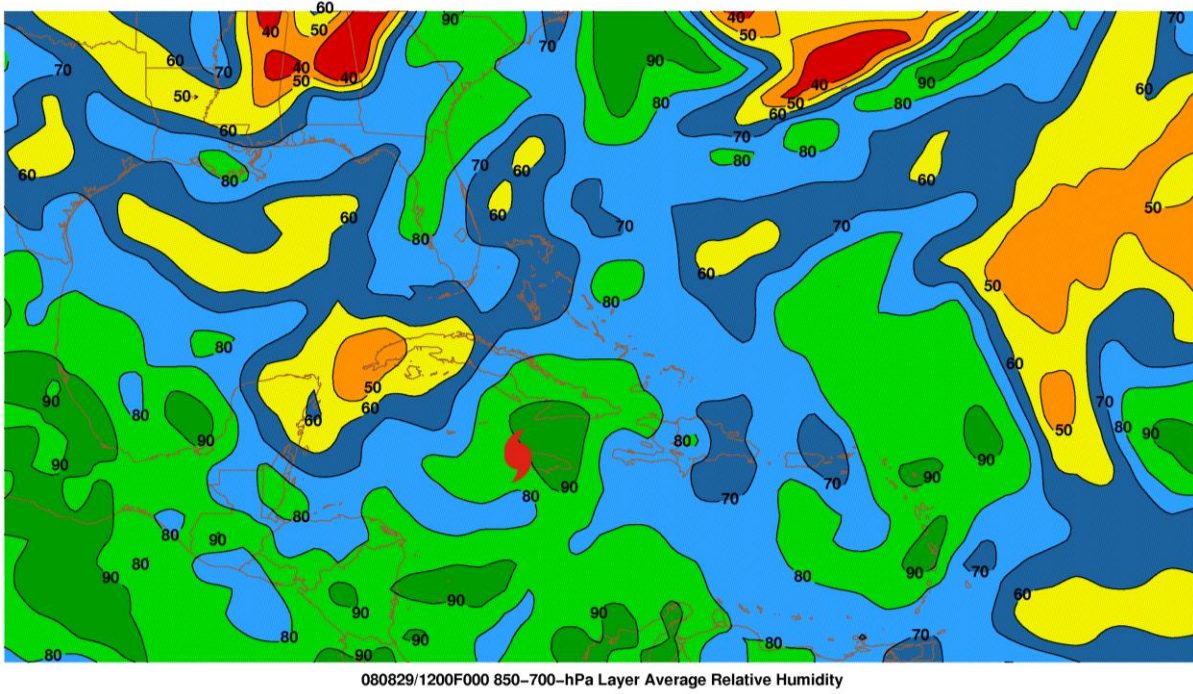
080829/1200F000 850-700-hPa Layer Average Relative Humidity

Figure 4. 850-700-hPa layer average relative humidity (%) at 1200 UTC 29 August 2008. Red hurricane symbol represents the central location of Gustav at 1200 UTC 29 August.
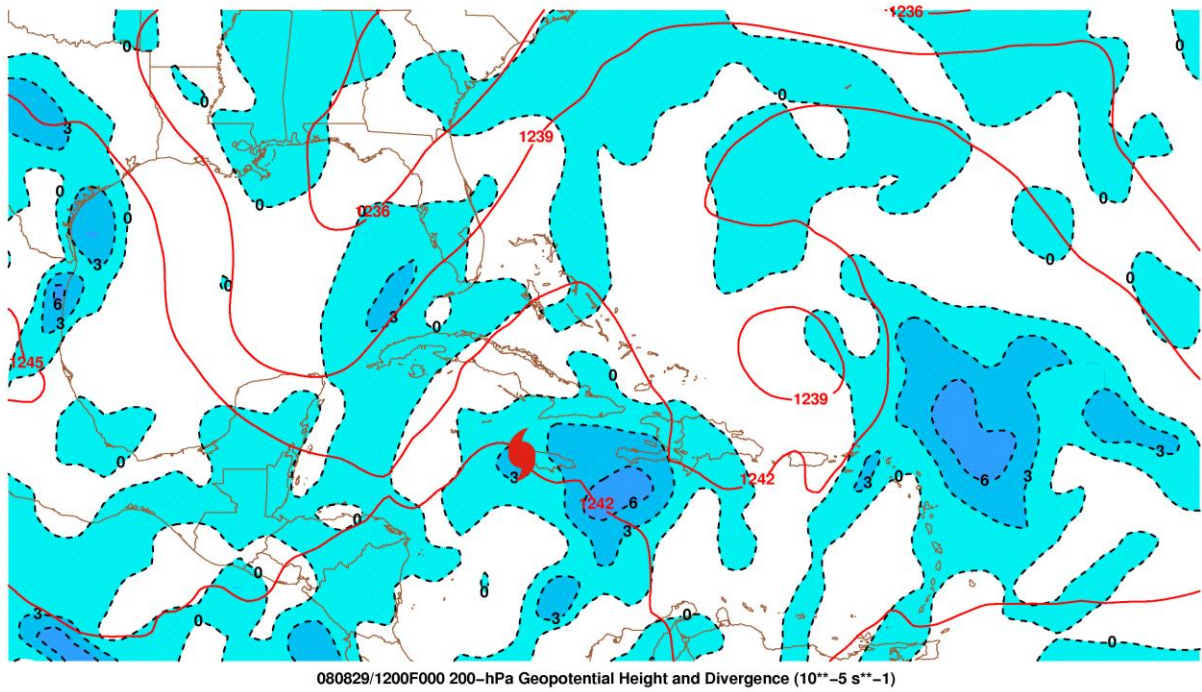
080829/1200F000 200-hPa Geopotential Height and Divergence (10**−5 s**−1)

Figure 5. 200-hPa divergence (10^{-5} s^{-1}) at 1200 UTC 29 August 2008. Red hurricane symbol represents the central location of Gustav at 1200 UTC 29 August.
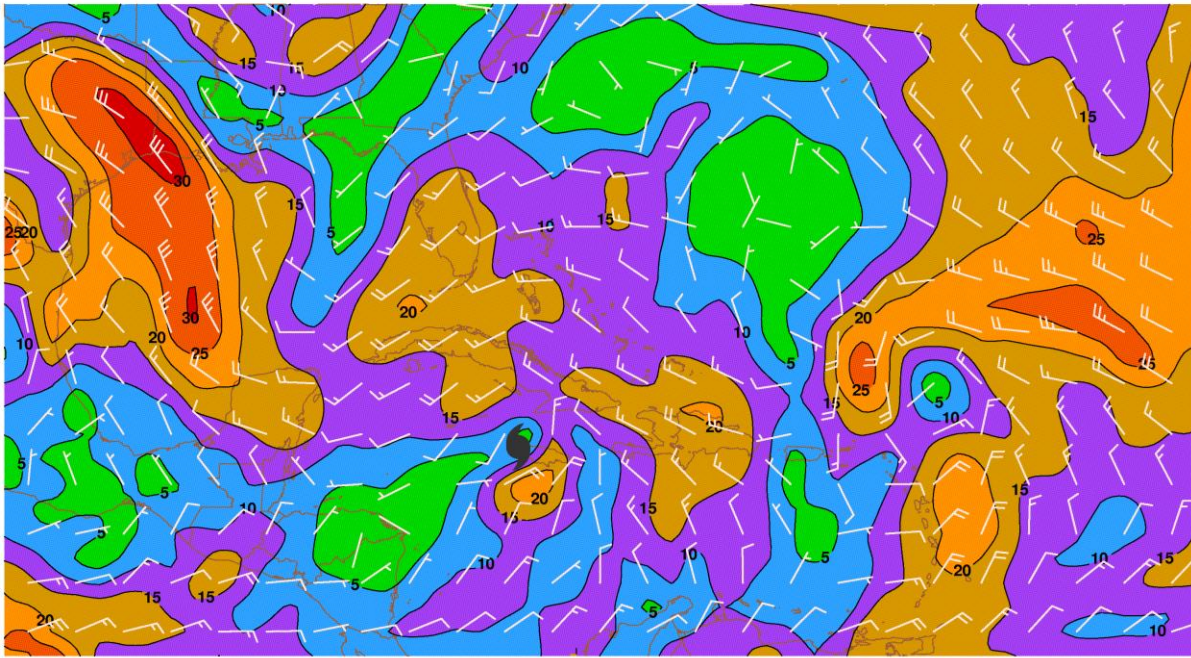
080829/1200F000 850–200–hPa Wind Shear

Figure 6. 850-200-hPa vertical wind shear magnitude (shaded; m s^{-1}) and vectors (barbs) at 1200 UTC 29 August 2008. Black hurricane symbol represents the central location of Gustav at 1200 UTC 29 August.
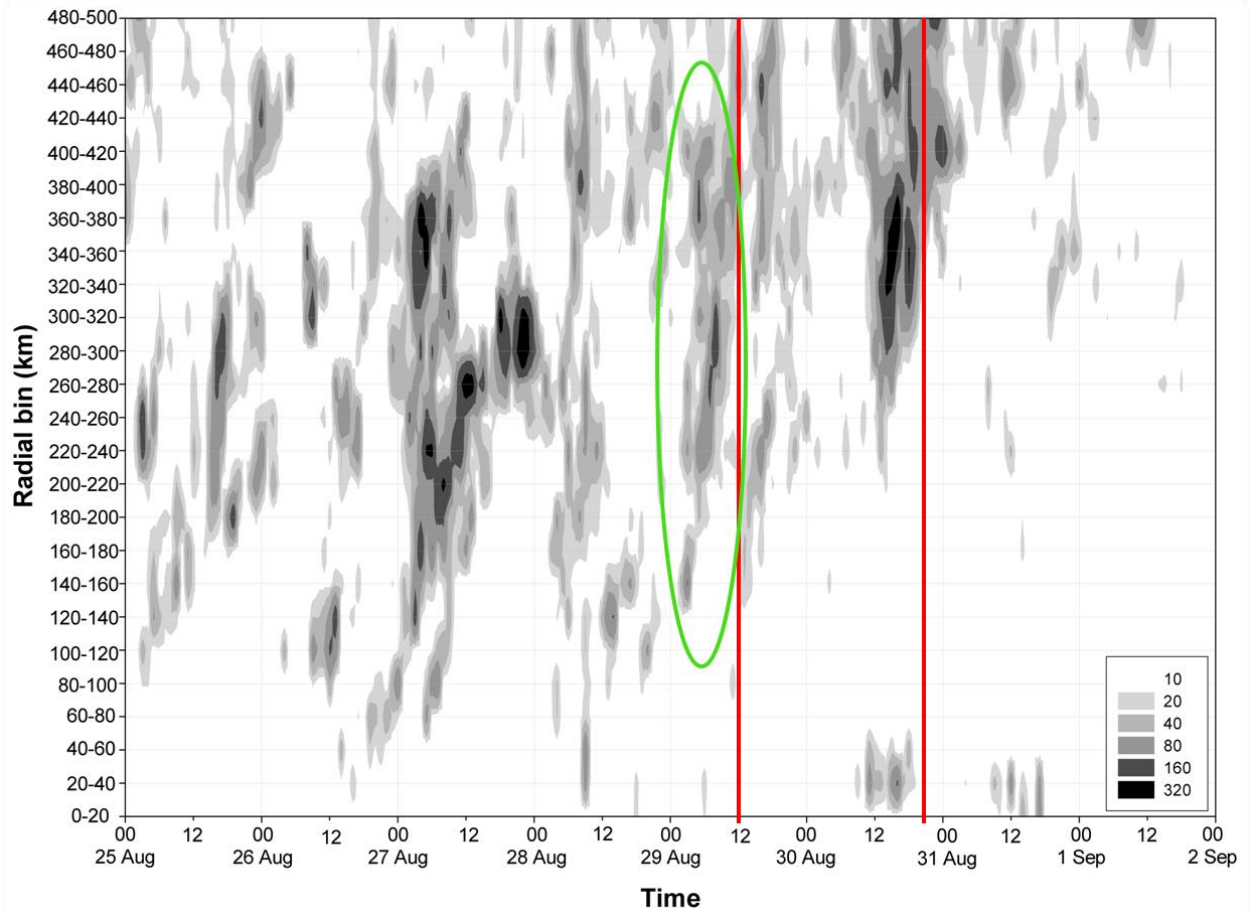
Figure 7. Hovmöller diagram of WWLLN flashes in 20 km radial bins from the center out to 500 km from 0000 UTC 25 August to 0000 UTC 2 September. Red lines denote the start and end of rapid intensification, respectively. Green ellipse highlights area and time of convection in Figures 8 and 9.
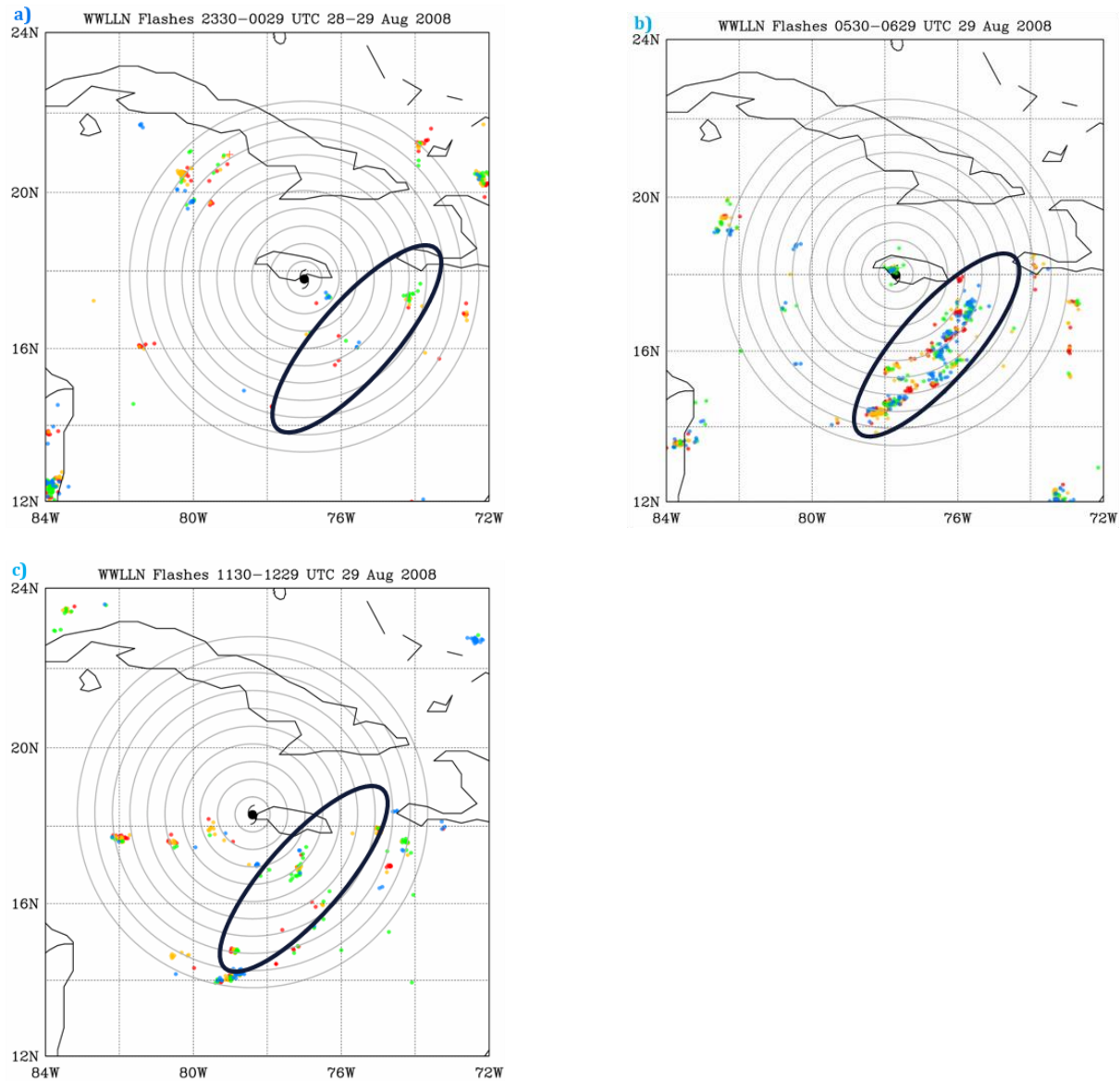
Figure 8. WWLLN flashes in the vicinity of TC Gustav at a) 0000 UTC; b) 0600 UTC; and c) 1200 UTC 29 August 2008 ± 30 min. Hurricane symbol denotes center of the storm at the time specified. Gray circles surrounding the center of the storm denote radii in multiples of 50 km from the center of the storm. Red dots denote flashes detected during the first 15 min of the hour specified. Green dots denote flashes detected during the second 15 min of the hour specified. Yellow dots denote flashes detected during the third 15 min of the hour specified. Blue dots denote flashes detected during the fourth 15 min of the hour specified. Black ellipse denotes convective area of focus.

a)

080829/0000F000 200-hPa Geopotential Height and Divergence (10**-5 s**-1)

b)

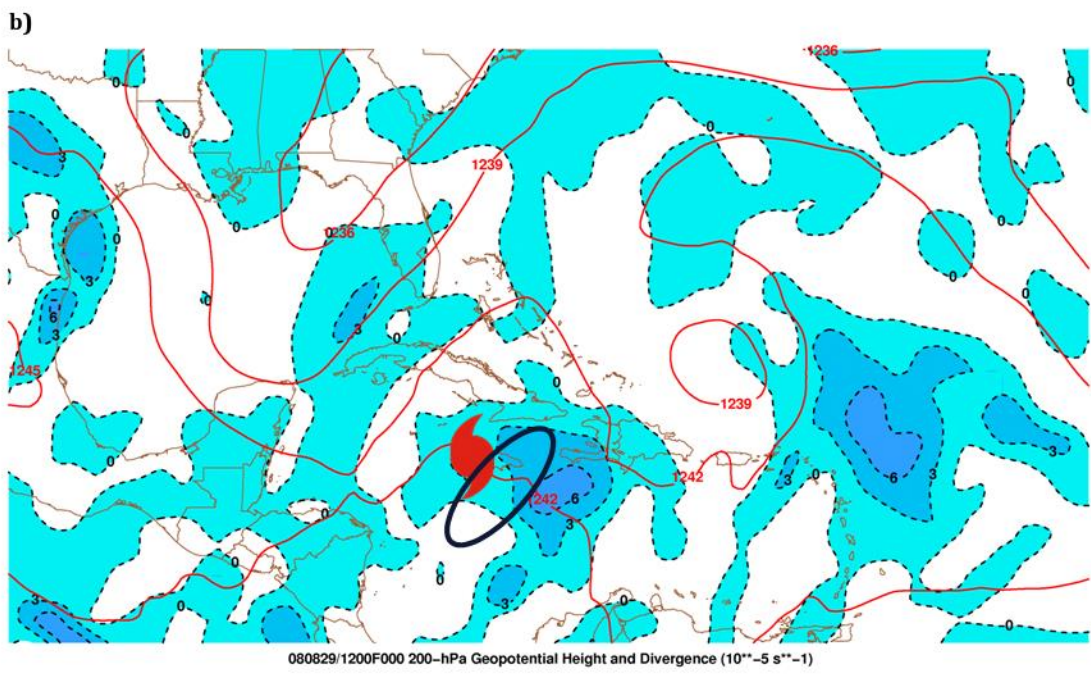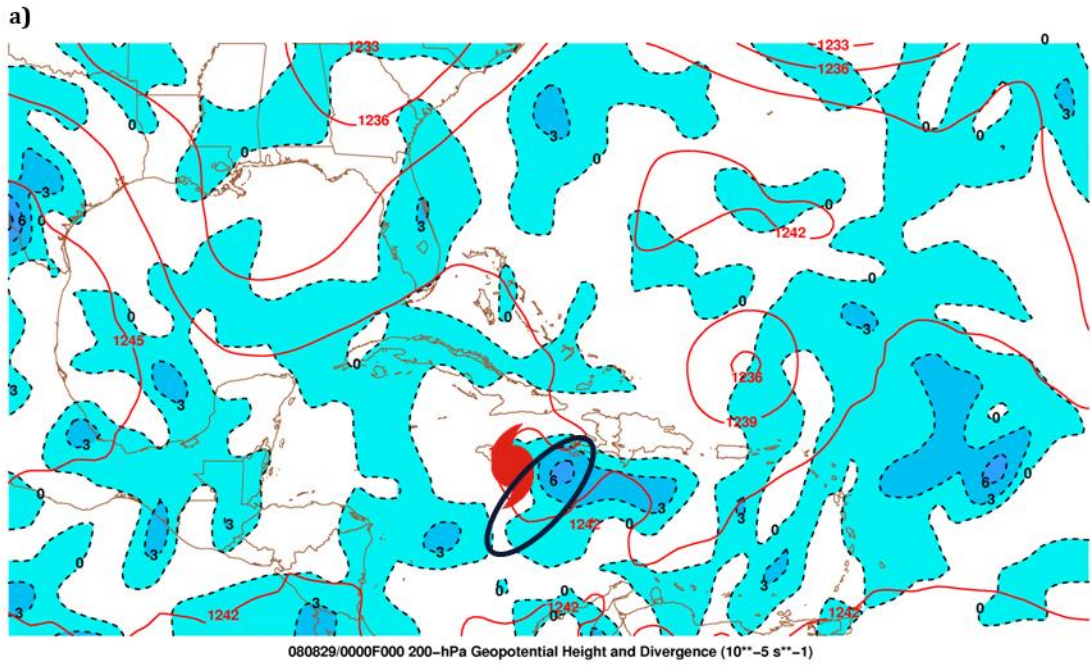080829/1200F000 200-hPa Geopotential Height and Divergence (10**-5 s**-1)

Figure 9. Same as Figure 5, except at a) 0000 UTC; and b) 1200 UTC 29 August 2008. Black ellipse denotes convective area of focus.