1.3 LIGHTNING AND RADAR OBSERVATIONS OF HURRICANE RITA LANDFALL

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1. INTRODUCTION

Los Alamos National Laboratory (LANL) owns and operates an array of Very Low Frequency/Low Frequency (VLF/LF) sensors that measure the electric field change waveforms emitted by Cloud-to-Ground (CG) and In-Cloud (IC) lightning. This array, the Los Alamos Sferic Array (LASA), has approximately 15 sensors concentrated in the Great Plains and Florida, which detect electric field changes in a bandwidth from 200 Hz to 500 kHz (Smith *et al*., 2002). Recently, LANL has begun development of a new dual-band sensor array that includes the Very-High Frequency (VHF) band as well as the VLF (Shao *et al*., 2006). Whereas VLF/LF lightning emissions can be used to deduce physical parameters such as lightning type and peak current, VHF emissions can be used to perform precise 3d mapping of individual radiation sources, which can number in the thousands for a typical CG flash (Rison *et al*., 1999). These new dual-band sensors will be used to monitor lightning activity in hurricanes in an effort to better predict intensification cycles. Although the new LANL dual-band array is not yet operational, we have begun initial work utilizing both VLF and VHF lightning data to monitor hurricane evolution. In this paper, we present the temporal evolution of Rita's landfall using VLF and VHF lightning data, and also WSR-88D radar. At landfall, Rita's northern eyewall experienced strong updrafts and significant lightning activity that appear to mark a transition between oceanic hurricane dynamics and continental thunderstorm dynamics.

In section 2, we give a brief overview of Hurricane Rita, including its development as a hurricane and its lightning history. In the following section, we present WSR-88D data of Rita's landfall, including reflectivity images and temporal variation. In section 4, we present both VHF and VLF lightning data, overplotted on radar reflectivity images. Finally, we discuss our observations, including a comparison to previous studies and a brief conclusion.

2. HURRICANE RITA

Rita reached tropical depression status on 18 September 2005 in the tropical Atlantic Ocean, just east of Grand Turk in the Turks and Caicos. It moved WNW, crossing between Cuba and Florida, achieving hurricane status on 20 September, about 100 nautical miles east-southeast of Key West, Florida. From here Rita moved into the Gulf of Mexico and strengthened rapidly, reaching category 5 status (on the Saffir-Simpson scale) over the Central Gulf of Mexico on 22 September. During the rapid intensification period, Rita's eyewall displayed abundant lightning (Shao *et al*., 2005). As Rita decayed while approaching the gulf coast, the eyewall lightning ceased. However, when Rita made landfall as a Category 3 storm (Knabb et al., 2006) near the Texas-Louisiana border at 0740 UTC on 24 September, the northern eyewall showed significant convective activity along with a resurgence in lightning. The following sections document this activity.

3. RADAR DATA

Fig. 1 shows horizontal and vertical cross sections of radar reflectivity from the KHGX (Houston) WSR-88D. The left panel was acquired at ~0600 UTC on 24 September, and the right panel was acquired at ~0740, the official time of landfall. The horizontal cross section is the reflectivity at 5 km altitude, and the locations of the vertical cross sections are indicated on the horizontal cross section as black lines. These two lines intersect at Rita's northern eyewall. At 0600 (left panel), a region of convection with high reflectivity (50-55 dBZ) is visible in the northern eyewall, extending to an altitude of 5 km, and the 5 dBZ echo cloud tops reach a maximum of about 13 km. At 0740 (right panel), the high-reflectivity region has grown considerably, extending to 10 km in altitude, and the 5 dBZ echo cloud tops reach nearly 20 km.

Fig 2. shows WSR-88D reflectivity contours of Rita's northern eyewall as a function of altitude and time, from 0400 to 0830 UTC on 24 September. Each time step represents a single column from successive 3d reflectivity cubes, acquired at approximately 6-minute intervals. Furthermore, each data column represents the same approximate location within Rita's eyewall. Although the contours show some "blobs" and "spikes," there is clear convective development with time, with a strong surge at landfall, ~0740. Note also the spike in the reflectivity contours at the same time and location. Although not visible in this particular plot, the maximum reflectivity in the eyewall reached 55-60 dBZ.

4. LIGHTNING DATA

4.1 VHF

Fig. 3 shows the latitude and longitude of all VHF lightning sources measured by the LDAR II network from 0100 to 1318 UTC on 24 September 2005. Superimposed on the plot is Rita's approximate ground track. The LDAR II network is composed of ~10 sensors circling the city of Houston with a network diameter of ~80 km (Ely *et al*., 2006). For nearby (~100 km) storms, VHF sensors will often record hundreds or even thousands of sources for a single CG flash, which can be displayed in a "connect-the-dots" fashion to

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visualize a single lightning flash in three dimensions. At landfall, Hurricane Rita's eyewall was approximately 300 km from the LDAR II network, well beyond the range of high-resolution coverage where full 3d maps of the lightning can be expected from the LDAR II network. As a result, there were only ~1000 measured VHF sources during this entire time period. However, the majority of these sources occurred between 0600 and 0900 and coincide with Rita's northern eyewall during landfall. In Fig. 3, there are four distinct clusters that lie on Rita's ground track. These clusters have been color coded in orange, green, red, and purple, and correspond roughly to the time periods 0245-0300, 0545-0645, 0715-0830, and 0930-1100, respectively. The average location of Rita's eye has been plotted with a square symbol for each of these time periods with the same color code. Fig. 4 shows a histogram of the number of VHF sources in Rita's eyewall during these four time periods. Note the spike in lightning events during the period of landfall.

In Fig. 5, we have plotted VHF lightning sources on top of the WSR-88D radar data for the time period from 0745-0750 UTC. Note that the lightning sources are coincident with the active convective region of Rita's northern eyewall. VHF lightning mapping arrays typically record multiple sources per flash; the 152 symbols thus do not necessarily represent 152 unique lightning flashes. However, it is clear that the lightning does indeed coincide with the active convection. Furthermore, the lack of sources near the ground suggests that these recorded VHF sources correspond to IC rather than CG lightning. Given the reduced detection efficiency of the LDAR II network at 300 km, it is not clear whether or not the apparent lack of CG sources is indicative of the actual IC/CG ratio in the eyewall. The next section will provide more information on this issue.

4.2 VLF/LF

In Fig. 6, we present VLF/LF lightning data from the LASA network plotted on top of WSR-88D data for the time period 0745-0750 UTC on 24 September. Prior to landfall (e.g., Fig. 1, left), LASA measured virtually no lightning flashes within the displayed geographic area. From 0745-0750 however, the period corresponding to Rita's landfall, LASA detected 49 different lightning flashes, a rate of 245 flashes per hour. Unlike the VHF, in which multiple sources are detected for a single flash, LASA sensors measure the vertical component of the radiated electric field change waveform, and a single point corresponds to a single lightning stroke. As before, the lower left panel is the horizontal cross section, and the upper left/lower right are vertical cross sections, corresponding to the black lines in the horizontal view. In particular, note that almost all of the observed lightning flashes fall within the region of strongest convection, the northern (soon to be defunct) eyewall. The upper right panel is the legend, and it shows that of the 49 detected flashes, there were 4 unclassified, 13 positive ICs, 3 negative CGs, 6 positive CGs, 16 positive fast pulse (FP), and 7 Narrow Bi-polar Events (NBE). An NBE is a high-energy, high-altitude, compact (in space and time) in-cloud discharge (Smith *et al*., 1999). An FP is akin to an NBE, but with a slightly "dirtier" waveform. So, of the 49 recorded flashes, 36 were in-cloud (IC) lightning. If we assume that the 4 unclassified flashes were CG, this gives an IC/CG ratio of 36/13 = 2.8. Thus, the VLF lightning flashes appear to be dominated by in-cloud lightning. Since detection efficiency for in-cloud lightning is generally less than for cloud-to-ground activity, it is likely that this ratio is an underestimate; the true ratio would likely be higher with all detection biases removed.

LASA was able to compute the altitude of 23 of the 49 flashes using reflections from the ionosphere. The events without available altitude information are plotted at ground level in the vertical cross sections. Looking at the VLF events with altitudes in Fig. 6, the average flash height is around 11 km. The opportunity to locate NBE lightning sources in altitude may be particularly useful in quantifying the vertical extent (strength) of the convective development and in possibly deducing vertical charge distributions. Also note that for the NBEs and FPs, the flashes appear to be offset from the center of convection by a few kilometers to the west, which is the prevailing wind direction in the northern eyewall. Also note that the NBEs and FPs lie well above the region of maximum reflectivity.

5. DISCUSSION AND CONCLUSION

Hurricanes are not normally strong lightning producers (Molinari *et al*., 1994, 1999). At Rita's landfall, however, abundant lightning was observed in the northern eyewall in both the VLF and VHF frequency bands. At 0600 UTC, prior to official landfall, the Convective Available Potential Energy (CAPE), computed from sonde-derived temperature and humidity profiles at Lake Charles, LA, was ~1570 J/kg. This amount of CAPE is considered moderately unstable (Holton, 1992). The authors are not aware of any vertical Doppler data of Rita's eyewall at landfall. Airborne 3d Doppler data were acquired over the Gulf of Mexico but ended prior to landfall. GOES IR imagery of Rita's landfall were available for determining cloud-top heights, but there were no obvious convective features in the region of the eyewall during this time period, presumably due to masking by cirrus blowoff. Thus, we were unable to deduce updraft speed of the convective motions responsible for the observed lightning. Roberts and Knupp (2004) measured a strong (~15 m/s) updraft feature during landfall of Hurricane Earl, but that updraft was associated with a rainband, not the eyewall.

We suggest that the convective updraft and lightning associated with landfall mark a transition between oceanic hurricane dynamics and continental thunderstorm dynamics as a result of convergence and suitable CAPE as the hurricane moved onto shore. At landfall, the eye shows signs of collapse, and overhead infrared imagery from the GOES satellite depict billowing features that are more typically seen in land-based thunderstorms. Also, lightning is a direct consequence of the electrification and breakdown processes that take place during the convective stages of thunderstorm development. Furthermore, strong vertical convective motions and an increase in radar reflectivity above the melting level are indicative of continental thunderstorm dynamics (Cecil et al., 2002).

In this paper, our goal was to document the phenomenology associated with Rita's landfall. In follow-up work, we plan to link our observations with a hurricane model such as HIGRAD (Guimond *et al*., 2009) to examine the breakdown in cyclonic flow and the transition to continental thunderstorm dynamics at landfall.

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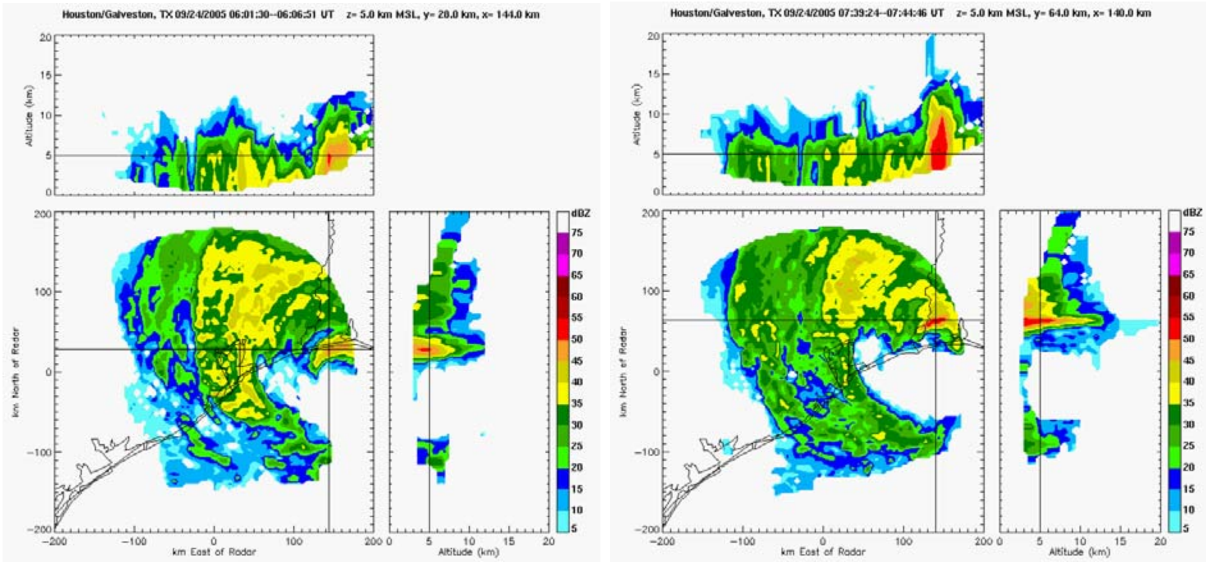

Figure 1. Horizontal and vertical radar reflectivity cross sections from the KHGX (Houston) WSR-88D. The left panel was acquired at 0600 UTC 24 September 2005, and the right panel was acquired the same day at 0740, the time of Hurricane Rita landfall.

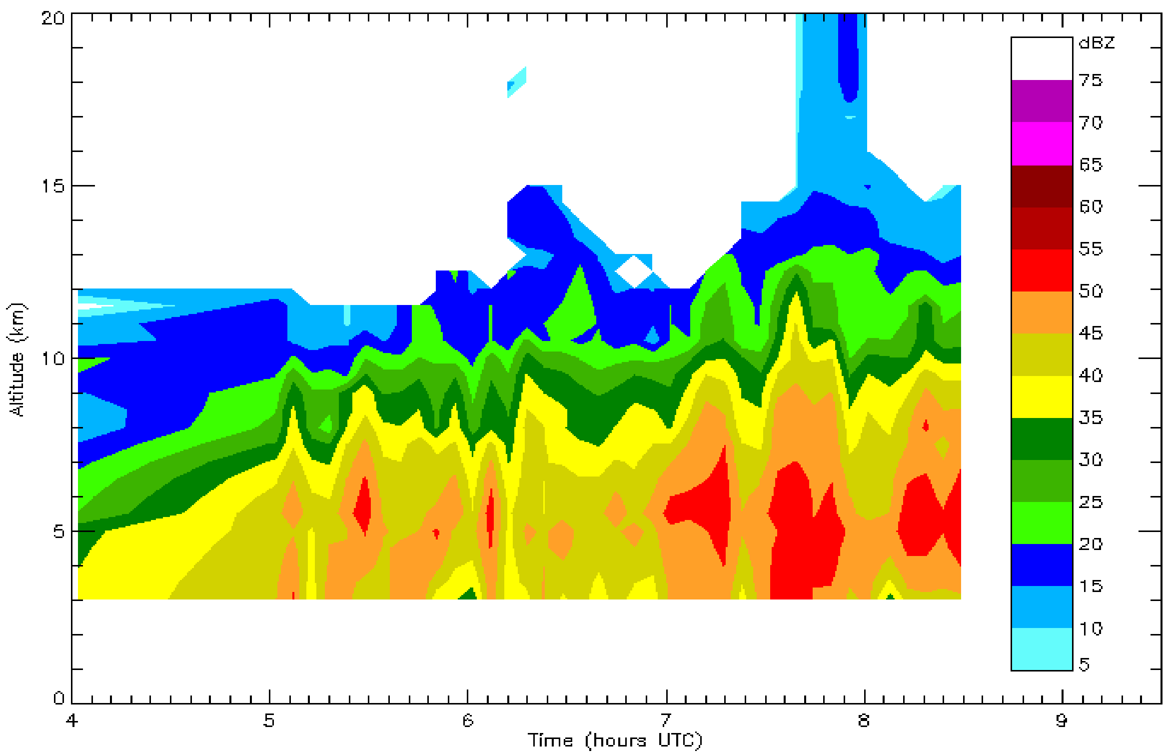

Figure 2. Radar reflectivity contours of Hurricane Rita's northern eyewall as a function of altitude and time on 24 September 2005. Each time step corresponds to a single vertical column from successive 3d radar reflectivity cubes. Rita landfall occurred at 0740.

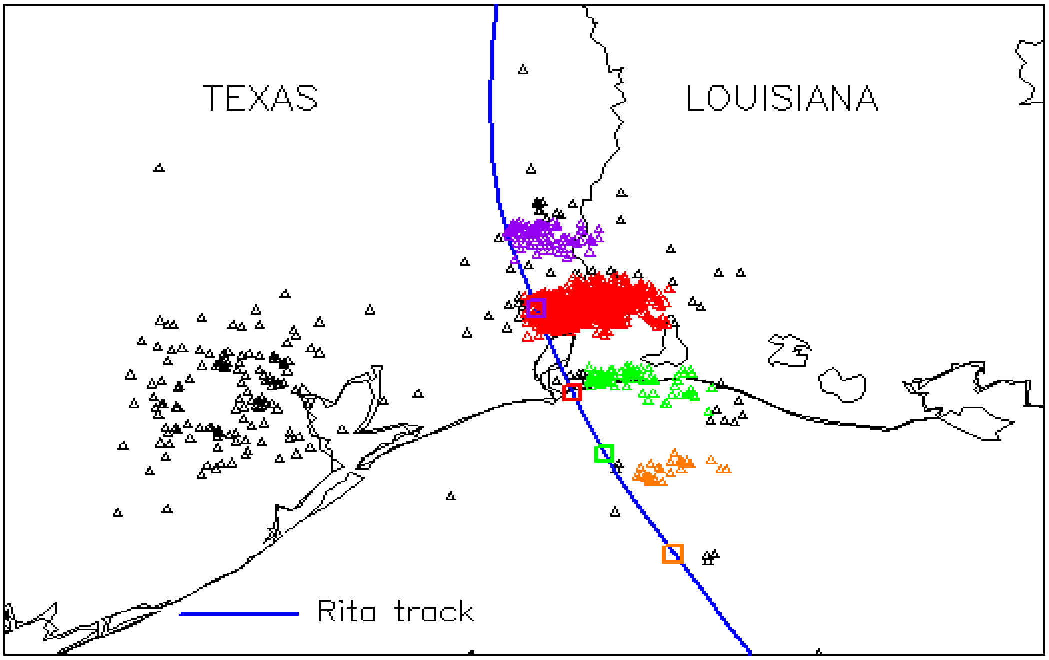

Figure 3. All VHF radiation sources detected by the Houston LDAR II network in the displayed geographic area during the time period from 0100 – 1318 UTC on 24 September 2005. Hurricane Rita's ground track is shown by the blue line. The colors orange, green, red, and purple correspond to the UTC time periods 0245-0300, 0545-0645, 0715-0830, and 0930-1100, respectively. The square symbols show the average location of Rita's eye during each time period.

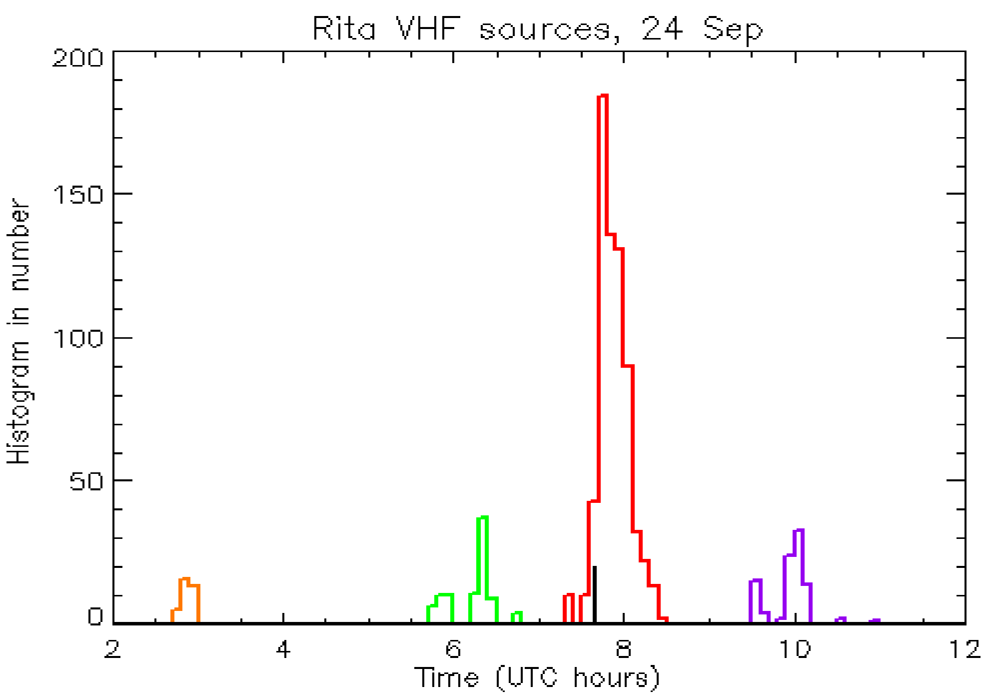

Figure 4. Histogram of the eyewall VHF radiation sources in Fig. 3. The vertical black line represents the time of Hurricane Rita landfall.

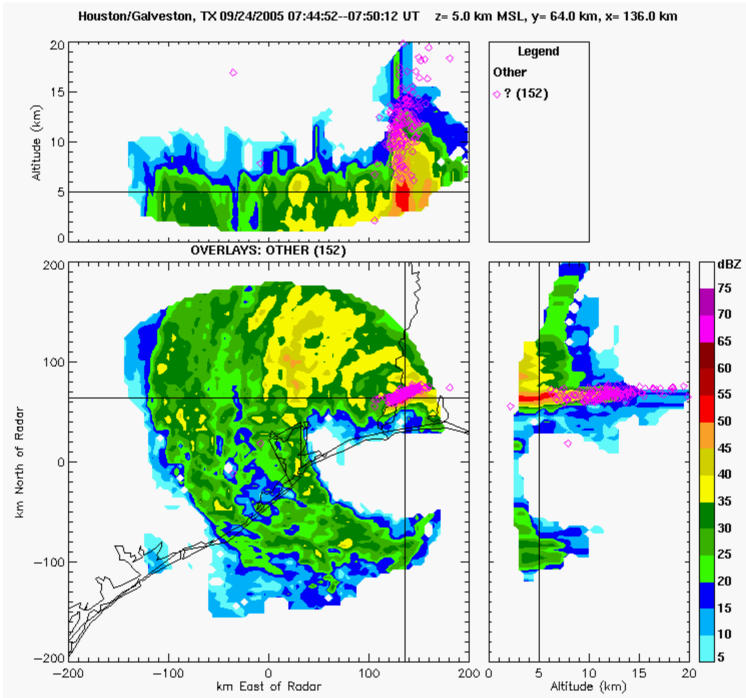

Figure 5. VHF radiation sources (pink diamonds), measured by the Houston LDAR II network, overplotted on radar reflectivity cross sections of Hurricane Rita at 0745 UTC 24 September 2005, the time of landfall. The horizontal cross section (lower left) corresponds to an altitude of 5 km. The locations of the vertical cross sections are represented by the two intersecting black lines.

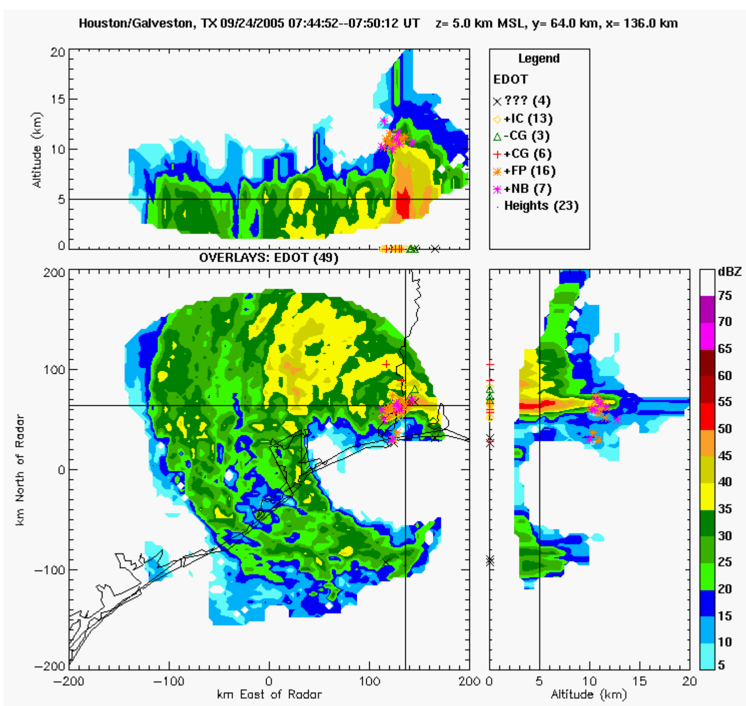

Figure 6. VLF/LF radiation sources (symbols), measured by LASA, overplotted on radar reflectivity cross sections of Hurricane Rita at 0745 UTC on 24 September 2005, the time of landfall. The horizontal cross section (lower left) corresponds to an altitude of 5 km. The locations of the vertical cross sections are represented by the two intersecting black lines.