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THERMODYNAMIC STRUCTURE OF TROPICAL CYCLONES DURING GENESIS

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1. INTRODUCTION

Prediction of tropical cyclone intensity change in a high vertical shear environment is challenging, especially during the formative stages. The problem is further compounded by the short timescales on which such systems can evolve. The present research showcases a storm that strengthened to a hurricane and subsequently weakened to barely tropical storm strength in less than twelve hours.

2. DATA AND METHODOLOGY

A multi-scale analysis of the environment and structure of Claudette (2003) before intensification to hurricane intensity and during the weakening phase is performed. The primary data sets utilized for this analysis include: National Centers for Environmental Prediction (NCEP) 1^{o}x1^{o} global analyses and European Centre for Medium-Range Weather Forecasts (ECMWF) 1.125^{o}x1.125^{o} global analyses to investigate the synoptic scale environment, and US Air Force reconnaissance data for diagnosing storm- and meso-scale aspects of the system structure. Infra-red (IR) satellite images, obtained from the Space Science Engineering Center at the University of Wisconsin-Madison, are also used to provide insight into the convective organization of the system.

The magnitude and direction of the 850-200hPa vertical wind shear is estimated by calculating the average wind within 500km of the storm center at each level. Both the NCEP and ECMWF analyses are used for this calculation to account for differences in how each model handles the tropical cyclone environment. Also, further uncertainty in the shear estimate can enter through differences in the observed and model center location. To quantify such possible errors, the NHC Best Track (BT) storm center and 850hPa vorticity maximum are used as possible center locations about which to calculate the shear. Both of these center locations are used for the calculation with the NCEP analysis. However, only the NHC BT center is used with the ECMWF analyses. Altogether, this gives three estimated shear values for each 6-hour analysis time.

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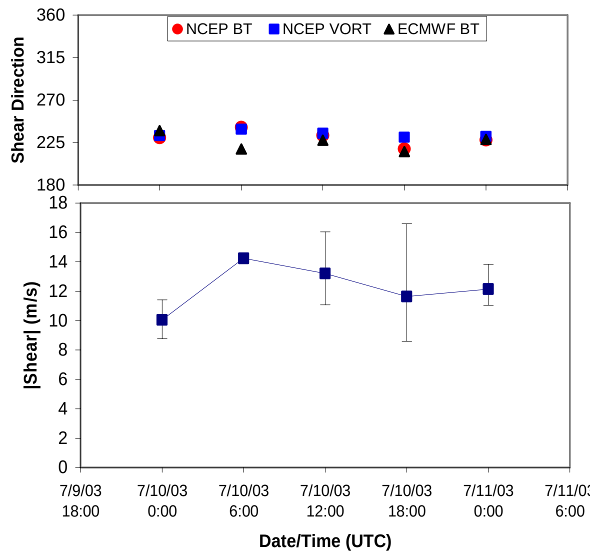

Figure 1 – 850-200hPa vertical wind shear direction (top) and magnitude (bottom) every six hours. Shear direction is shown for NCEP and ECMWF analyses based on NHC BT center (red circles and black triangles, respectively), and for NCEP analysis centered on 850hPa vorticity maximum (blue squares). For shear magnitude the average value of the three methods is shown by the blue squares. The error bars indicate the maximum and minimum values of shear calculated from any of the three methods.

3. OBSERVATIONS AND DISCUSSION

The magnitude and direction of the 850-200hPa vertical wind shear from 00 UTC 10 July to 00 UTC 11 July is shown in Figure 1. At each of the analysis times, the shear direction estimated by each of the three methods is similar. The shear was consistently directed from the southwest throughout the period shown. The magnitude of the vertical shear estimated by the three methods does vary over this period. In addition to the temporal shear variations, the magnitude of the shear at any of the analysis times can vary greatly between the different methods (e.g., 18 UTC 10 July), as indicated by the error bars. In general, the uncertainty in the shear direction is small, but in shear magnitude is large. Despite this large uncertainty, the shear clearly remains high throughout the period, generally >10ms^{-1}.

Figure 2 shows IR satellite images at 12-hour intervals from 00 UTC 10 July to 00 UTC 11 July. At 00 UTC on 10 and 11 July, the deepest convection was displaced downshear (towards the northeast) of the BT storm center (indicated by the white tropical storm symbol).

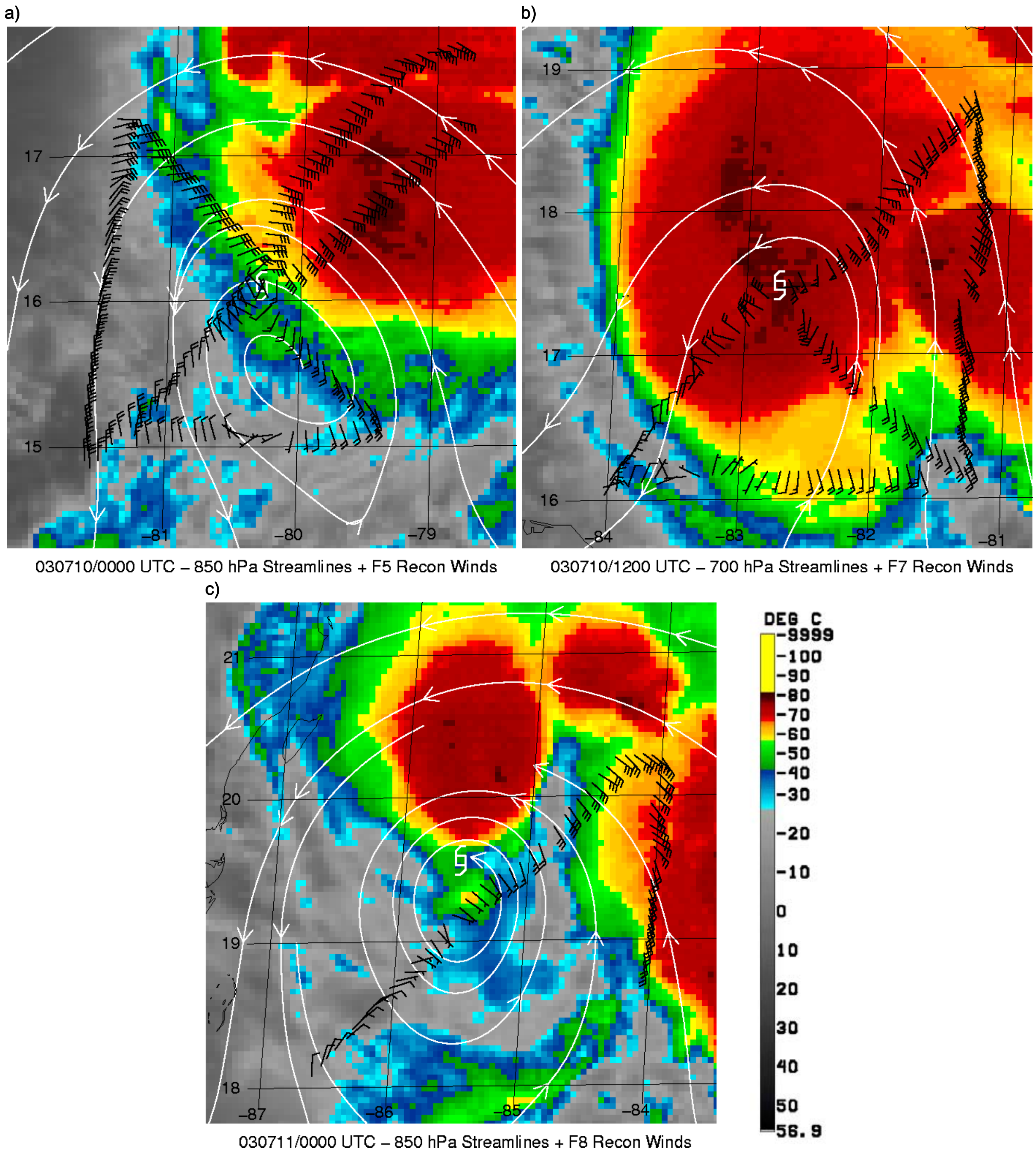

Figure 2 – Aspects of storm-scale structure. IR satellite imagery (from 15 minutes after each analysis time) overlain with streamlines from the NCEP gridded analyses (white lines with arrows) and US Air Force reconnaissance winds (black barbs) at, a) 850hPa at 00 UTC 10 July, b) 700hPa at 12 UTC 10 July, and c) 850hPa at 00 UTC 11 July. The location of the NHC BT centre at each of the analysis times is indicated by the white tropical storm symbol. The reconnaissance winds are total observed wind, i.e., not storm-relative. Only observations made within 3 hours of the analysis times are included. Each wind observation has been relocated relative to the moving storm centre to give a composite view of the storm structure. Therefore, the latitude and longitude lines do not apply to the reconnaissance observations. A color bar is provided as guide to the color enhancement used on the satellite images.

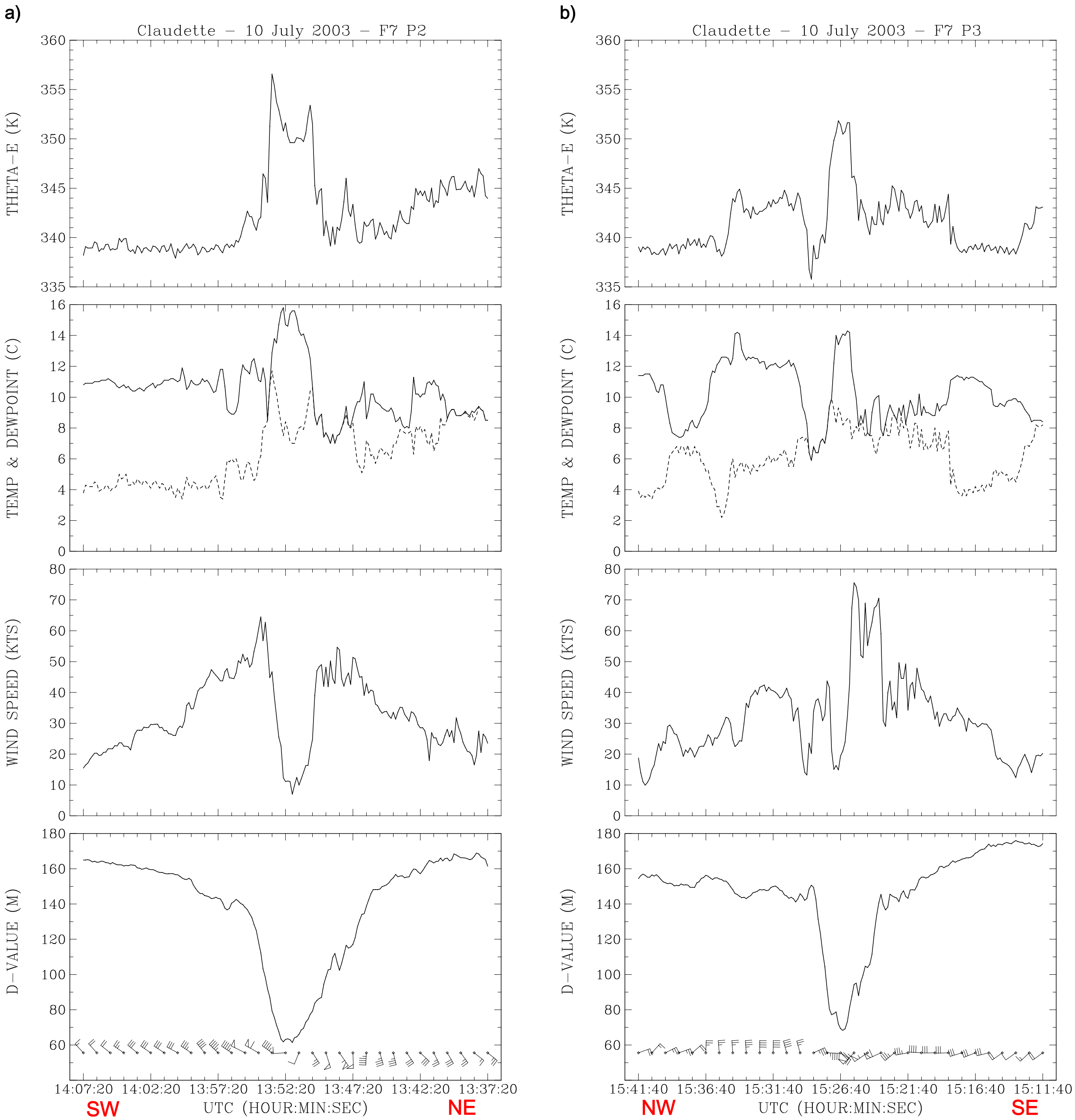

Figure 3 – Time-series of 700hPa flight-level observations from a US Air Force reconnaissance flight through the centre of Claudette at a) ~1352 UTC, and b) ~1526 UTC 10 July 2003. Variables shown are θ_e (K; solid line; top panel), temperature (solid line) and dewpoint (dashed line; both ^{o}C and 2nd from top panel), storm-relative wind speed (solid line; knots; 3rd from top panel), D-value (solid line; m; bottom panel) and storm-relative winds (barbs, half barb is 5 knots, full barb is 10 knots, flag is 50 knots; bottom panel). The red labels along the base of each figure indicate the direction of each pass through the storm center. Note that the time axis for both figures is reversed, with the eastern-most observations on the right-hand side of each panel. The horizontal distance represented by each 30-minute time-series is approximately 180km.

This convective signature was a direct result of the high shear environment, and exemplifies the convective structure present for the majority of the life time of Claudette. This structure is consistent with the results of other observational studies of sheared systems (e.g., Black et al 2002 and Corbosiero and Molinari 2002). At 12 UTC 10 July, however, the deepest convection was located *at* the storm center. It is at this time that Claudette was upgraded to a hurricane.

Overlain on each of the IR images in Figure 2 are streamlines (white lines with arrows) from the NCEP analyses and reconnaissance (hereafter recon) winds (black barbs) from flights that took place close to the analysis times. The broad-scale wave-like structure of the system is evident in the recon winds at 00 UTC (Fig. 2a) and 12 UTC (Fig. 2b) 10 July. The NCEP analysis appears to capture this structure well. Unsurprisingly the NCEP analysis is unable to resolve the much smaller scale of the central circulation of Claudette at 00 UTC and 12 UTC 10 July (located close to the BT center). The recon winds presented in this manner are also unable to fully show the size and strength of the hurricane vortex at its peak.

Figure 3 shows time series of storm-relative wind and various thermodynamic variables at 700hPa for 30-minute periods centered on the time at which the aircraft passed through the center of the system. In Figure 3a, the aircraft passed through Claudette from northeast to southwest approximately 2 hours after the system became a hurricane. The eye and eyewall are easily identifiable in the temperature and dewpoint fields, with the eye characterized by warm (16^{o}C) and dry (dewpoint depression ~8-10^{o}C) air, and the eyewall by relatively warm (~10^{o}C) and saturated air. The air in the eyewall also had the highest θ_e (~355K), with slightly lower (~5K) θ_e values found in the eye. The saturated eyewall was also located just radially inside the radius of maximum wind (RMW) on both sides of the storm. On the upshear (southwest) side of the storm, literally just beyond the saturated eyewall, the air was dry (dewpoint depression ~6^{o}C), resulting in very low θ_e values (<340K) there.

Figure 3b shows the next pass through the center of Claudette (from southeast to northwest), approximately 90 minutes later. In the θ_e time series, it appears that the very high θ_e values in the saturated eyewall had disappeared, although the relatively high values in the eye were still present. At this time, there was also dry air (dewpoint depressions ~6^{o}C) located to the left and right of the shear vector, outside the RMW. Another 90 minutes after this pass through the storm center, the US Air Force recon plane struggled to find a circulation at 700hPa. The 850hPa recon wind observations shown in Fig. 2c at ~00 UTC 11 July indicate that even a weak circulation was difficult to find 6 hours later.

It is hypothesized that a Rossby wave on the radial vorticity gradient at the RMW allowed for the low θ_e air upshear to be mixed into the eyewall. As the dry air was entrained into the eyewall, cold downdrafts would have been initiated. As these downdrafts reached the boundary layer, the high θ_e energy source would have been cut off, leading to rapid weakening of the overturning circulation, and a rapid spin-down of the primary circulation. Essentially, once dry air is directly adjacent to the eyewall, any disturbance within the eyewall vorticity gradient will mix dry air inward.

This case study exemplifies the necessity for caution expressed by Dvorak (1975) when dealing with sheared tropical cyclones. The pulsation of convection over the center of Claudette on a timescale a few hours, which occurred for several days prior to the system reaching hurricane intensity, could perhaps have been a warning sign of what was to come. When the deep convection occurred at the storm center, and remained there for a few hours, rapid intensification occurred. However, the high shear environment still meant that the hurricane was ultimately doomed, as the presence of the dry air upshear was a direct result of the shear. Hence, equally rapid weakening also occurred. Such systems pose a real problem for forecasters when trying to predict and warn of rapid intensity changes.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

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