2C.6 AN ANALYSIS OF THE TROPICAL CYCLONE CIRRUS CANOPY USING HS3 AND TCI OBSERVATIONS

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1. INTRODUCTION

Tropical cyclones (TCs) are characterized by a horizontally-extended area of clouds known as the “cirrus canopy.” This region of cold cirrus is formed as intense convection lofts condensate into the upper troposphere and lower stratosphere, where it affects its immediate environment through latent heating and interaction with radiation. An increasingly large body of work shows that physical processes within the cirrus canopy can feed back onto the storm circulation and affect its track, size, and intensity (e.g. Fovell et al. 2009; Bu et al. 2014). Until recently, however, the structure of the TC cirrus canopy has not been well-observed.

Observations from the NASA Hurricane and Severe Storm Sentinel (HS3) and Office of Naval Research Tropical Cyclone Intensity Experiment (TCI) provide analyses of the TC cirrus canopy with unprecedented spatial resolution. These observations reveal striking upper-tropospheric variability in TCs that might reflect important processes occurring within and around the cirrus canopy.

2. DATA AND METHODS

2.1 *HS3 and TCI observations*

Dropsonde observations from HS3 and TCI are used to analyze the upper-tropospheric temperature profile of TCs. Since these sondes were deployed from the lower stratosphere, the complete upper-tropospheric structure can be observed. These soundings are interpolated to a uniform vertical grid with 100-m grid spacing, as in Molinari et al. (2014). The height and temperature of the cold point tropopause – defined as the coldest point in the sounding – will be analyzed, along with vertical cross sections along flight legs from HS3 and TCI.

2.2 *Idealized modeling*

To determine the potential causes of the observed upper-tropospheric variability, an idealized axisymmetric simulation of a TC was conducted using Cloud Model 1 (CM1; Bryan and Rotunno 2009). The integration was performed on a domain 6000-km-wide and 25-km-deep, with constant horizontal and vertical grid spacing of 1 km and 250 m, respectively. Thompson microphysics was employed along with the NASA-Goddard radiation scheme for both longwave and shortwave radiation. A TC was spun up using the initial vortex and base state sounding of Rotunno and Emanuel (1987) on an *f* plane with a constant sea surface temperature of 28°C.

3. RESULTS

3.1 *The upper-tropospheric temperature structure of Nadine (2012)*

HS3 conducted a flight into TC Nadine on 14 September, 2012, as Nadine intensified from tropical storm to hurricane strength. Dropsondes were deployed along a number of flight legs over the storm, revealing dramatic upper-tropospheric variability across the cirrus canopy.

Fig. 1 shows the drop locations of two sondes that were deployed during one of the transects across the cirrus canopy, along with their observed soundings. The dropsonde deployed just outside the cirrus canopy (Fig. 1b) observed a nearly dry-adiabatic lapse rate between about 130 and 170 mb and a smooth temperature transition from the upper troposphere to the lower stratosphere. In contrast, a sonde deployed within the cirrus canopy (Fig. 1d) reveals a distinct temperature inversion just above 150 mb and a sharp transition from the upper troposphere to the lower stratosphere near 120 mb. This thermodynamic profile – characterized by a stable layer near 150 mb (about 14-15 km altitude) – was not localized; rather, it was observed throughout a broad region of the cirrus canopy (Fig. 2). Interestingly, though, this double stable layer structure was confined almost exclusively to the

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region of cold infrared brightness temperatures (T_b).

3.2 *The relationship between infrared brightness temperature and upper-tropospheric static stability*

To further investigate the relationship between the upper-tropospheric temperature profile and T_b, a large number of HS3 dropsonde observations were analyzed. Each sounding was visually examined and subjectively classified into three different categories by upper-tropospheric temperature structure: 1) Smooth profile, 2) Sharp profile, and 3) Multiple stable layer profile. Examples of each of these categories are shown in Fig. 3. A T_b was assigned to each sounding using the value observed in GOES imagery at the drop location.

Cumulative distributions of T_b are plotted in Fig. 4 for each of these three categories. The “sharp” and “multiple” distributions are nearly identical, indicating that these two upper-tropospheric profiles tend to occur in similar cirrus environments. The “smooth” profile’s distribution, however, indicates that this type of profile is much more common in warm T_b than in cold T_b, and much less common than “sharp” or “multiple” profiles in cold T_b. These distributions suggest that “sharp” and “multiple” profiles tend to be associated with the presence of cold cirrus.

3.3 *Preliminary modeling results*

The CM1 simulation described in section 2.2 exhibits upper-tropospheric temperature structures similar to those observed in the HS3 soundings. Fig. 5 shows the temperature and dew point profiles at a radius of 250 km in the simulated TC after it had intensified into an intense hurricane. Like the structure observed in Nadine (2012), this double stable layer was horizontally extensive – spreading across a region greater than 100-km-wide.

The output from this simulation is currently being analyzed – using Lagrangian heat budgets and lapse rate tendencies – to determine what mechanisms led to the development of the double stable layer. If the model accurately simulates the physical processes occurring in the cirrus canopies of real TCs, these analyses might illuminate the causes and potential implications of these upper-tropospheric temperature structures.

3.4 *Preliminary TCI observations*

In a preliminary analysis of TCI dropsonde observations, large upper-tropospheric variability was observed in Hurricane Patricia (2015). Two transects were flown through the eye of Patricia on 22 October, 2015, while it was undergoing rapid intensification. As expected, the maximum upper-tropospheric potential temperature occurred in the eye (Fig. 6). During the 45 minutes that elapsed between the two center crossings, the potential temperature at the cold point tropopause within the eye increased by 14°C. This evolution is consistent with the descent of stratospheric air into the upper troposphere (e.g. Chen and Zhang 2013), and is the subject of ongoing investigation.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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6. FIGURES

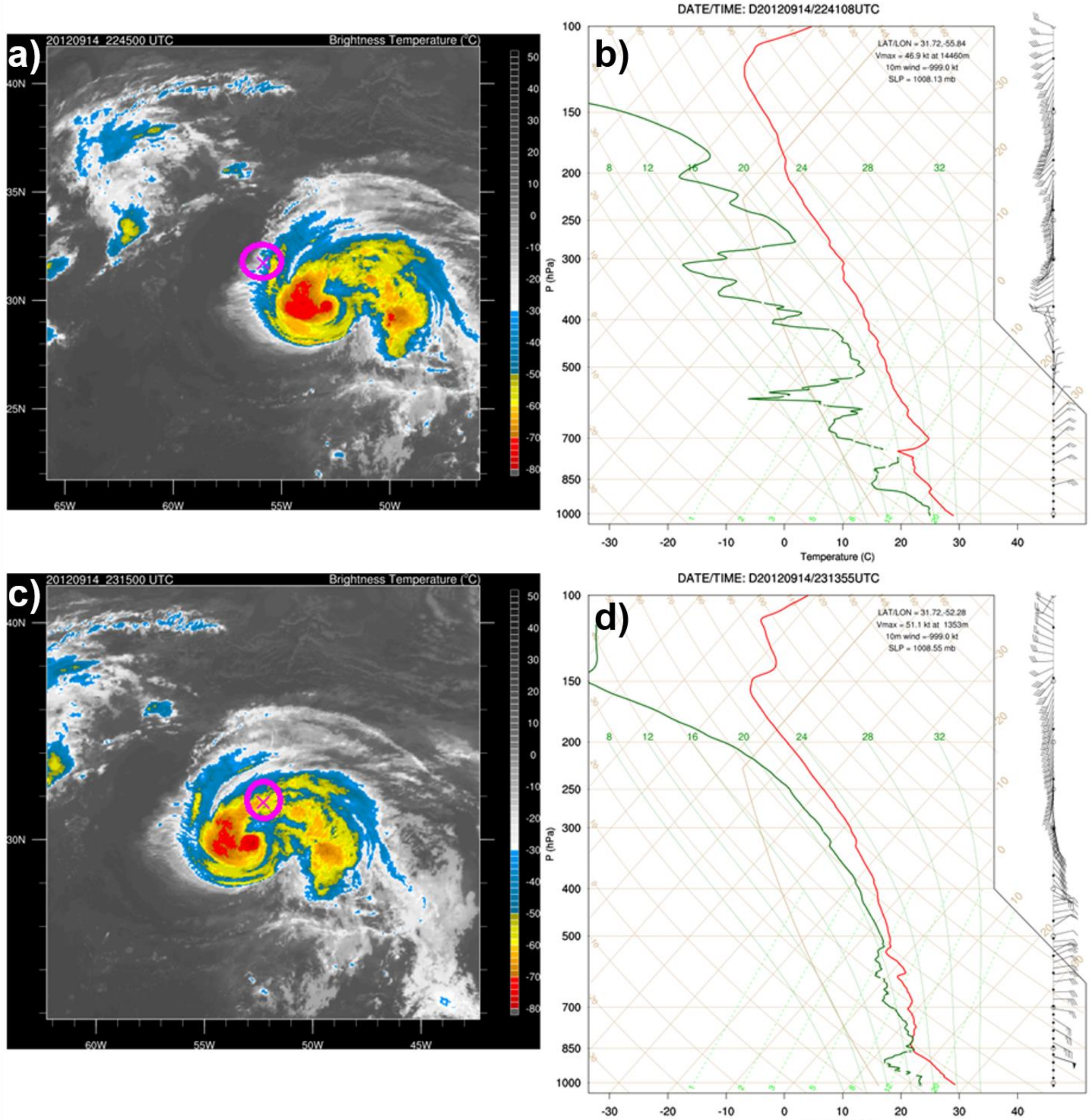

Figure 1. *Infrared brightness temperatures (a,c) and skew-t plots (b,d) for two dropsondes deployed in Hurricane Nadine on 14 September, 2012. The magenta circles in (a) and (c) indicate dropsonde deployment locations.*

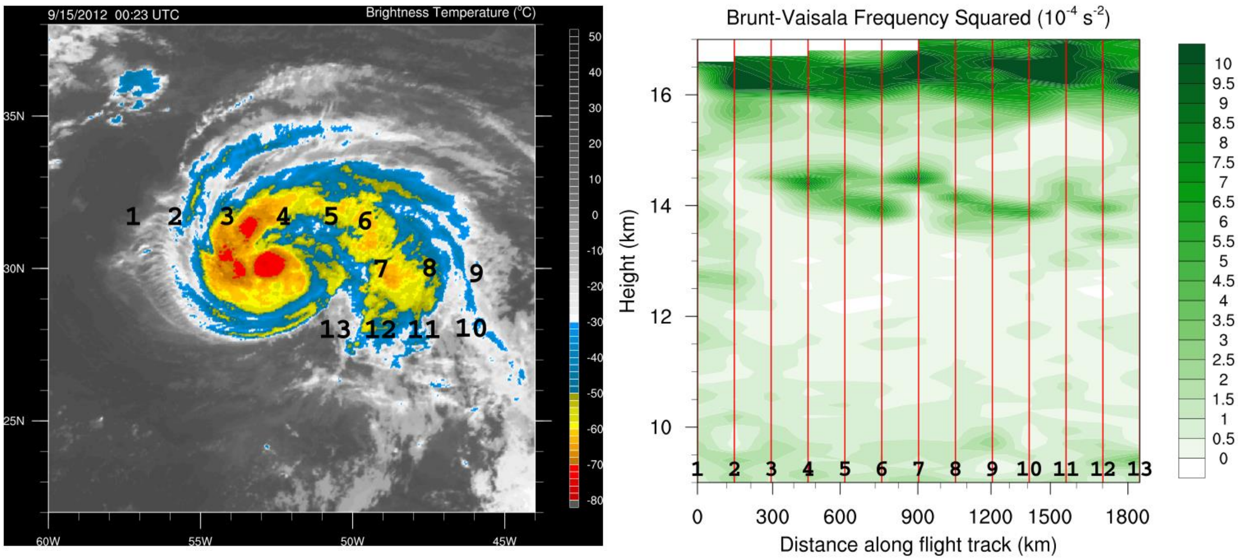

Figure 2. Infrared satellite image of Hurricane Nadine on 15 September 2012 (left) and a vertical cross-section of the Brunt Väisälä frequency squared (N^2; 10^{-4} s^{-2}) over a portion of the flight (right). The numbers on the satellite image indicate dropsonde deployment locations, which correspond to the red lines in the N^2 plot.

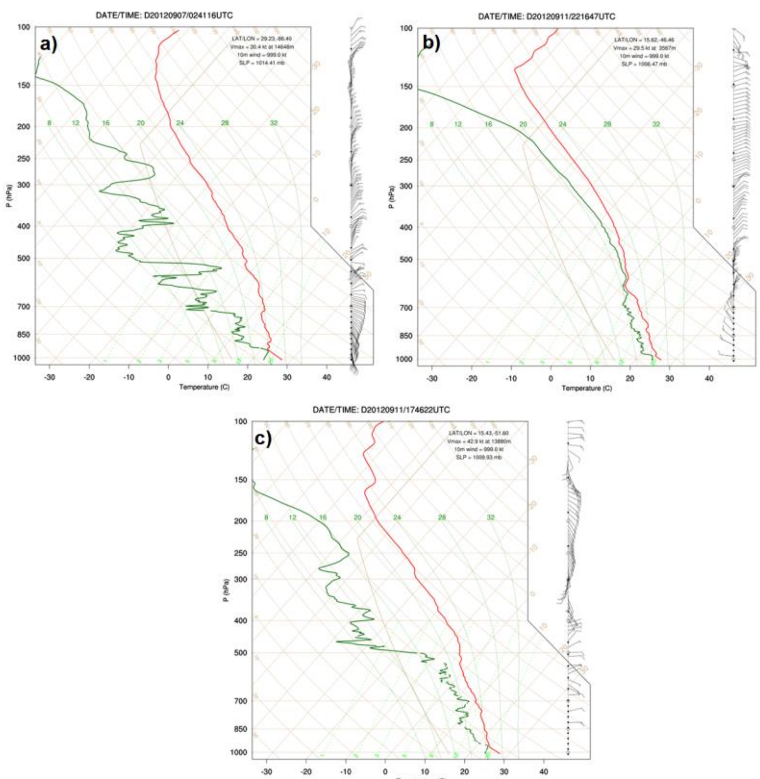

Figure 3. Skew-t examples of (a) smooth, (b) sharp, and (c) multiple stable layer temperature profiles from the HS3 dropsonde dataset.

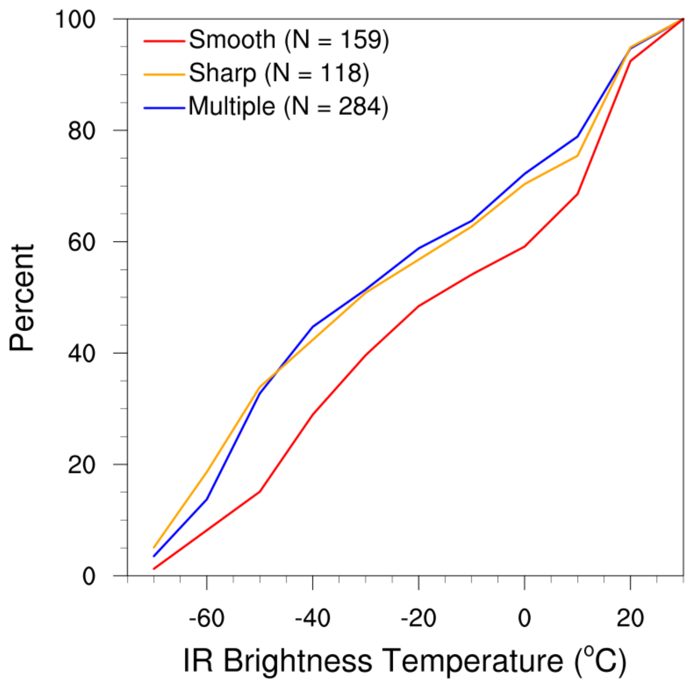

Figure 4. Cumulative distributions of infrared brightness temperature for the three upper-tropospheric temperature profile categories shown in Fig. 3.

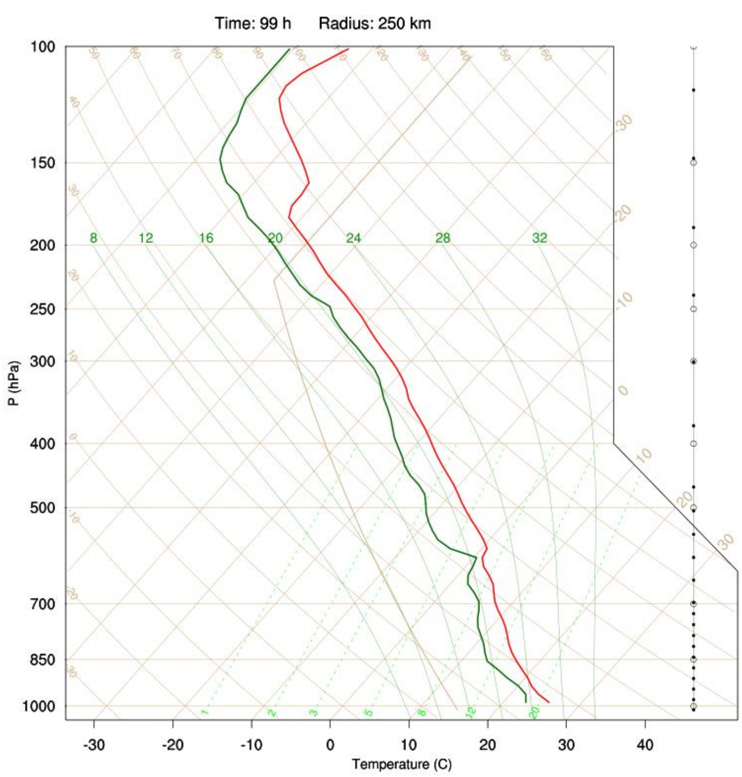

Figure 5. Skew-t plot from an idealized, axisymmetric CM1 simulation of an intense tropical cyclone at a radius of 250 km.

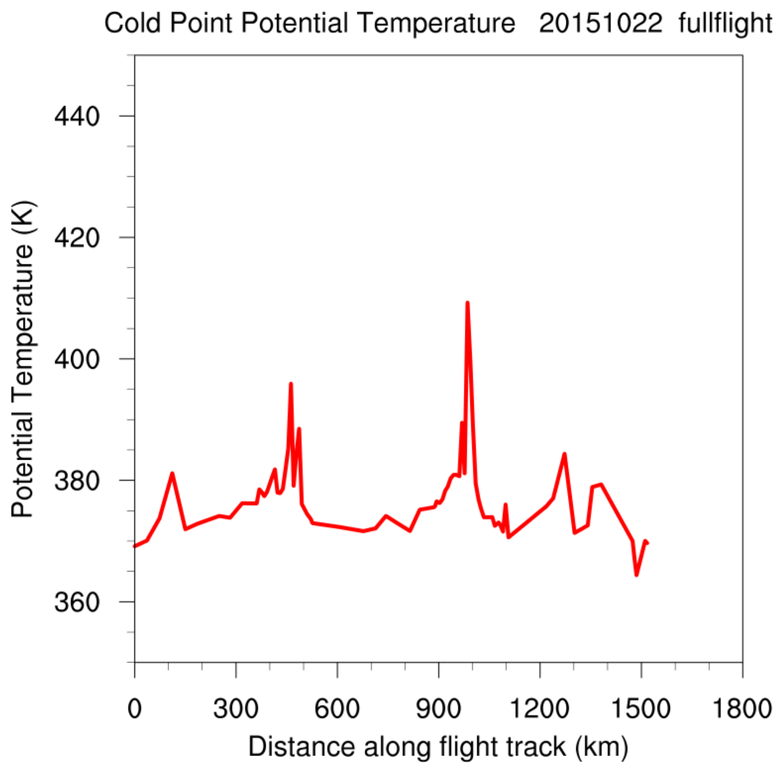

Figure 6. Potential temperature at the cold point tropopause (K) along two transects through the cirrus canopy of Hurricane Patricia on 22 October, 2015.