Tall precipitation cells in tropical cyclone eyewalls are associated with tropical cyclone intensification

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[1] The association of tall precipitation with tropical cyclone intensification may have implications for the difficult task of forecasting the destructive potential of tropical cyclones. This study uses all of the well-centered overflights of tropical cyclones from 1998 to 2003 seen by the TRMM Precipitation Radar. The chance of intensification increases when one or more extremely tall convective towers exist in the tropical cyclone's eyewall. We define an extremely tall convective tower as a convective cell with a 20 dBZ reflectivity signal that reaches an altitude of at least 14.5 km. In addition, we adapt this radar technique for use with more plentiful infrared and passive microwave data. *INDEX TERMS:* 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3360 Meteorology and Atmospheric Dynamics: Remote sensing. **Citation:** Kelley, O. A., J. Stout, and J. B. Halverson (2004), Tall precipitation cells in tropical cyclone eyewalls are associated with tropical cyclone intensification, *Geophys. Res. Lett.*, *31*, L24112, doi:10.1029/2004GL021616.

1. Introduction

[2] After decades of research, meteorologists still have limited success when forecasting tropical cyclone intensity [*Kaplan and DeMaria*, 2003]. Intensity provides an estimate of a tropical cyclone's destructive potential were it to strike land. Intensity is usually stated as the maximum one minute, sustained, surface wind speed. Forecasters make official intensity predictions based on statistical models, dynamic models, and direct examination of observations [*DeMaria and Kaplan*, 1999].

[3] To help predict intensification, several researchers suggest looking for evidence of strong convective rain near the eye [*Rodgers et al.*, 2000; *Steranka et al.*, 1986; *Simpson et al.*, 1998].

[4] In this paper, we propose a slightly different technique: find the tallest convective cell in the eyewall. Section 3 presents the statistical justification for looking at the height of convection when predicting tropical cyclone intensity. Next, we make use of this statistical evidence to construct a definition of "extremely tall" convective towers. Section 4 shows how effective this definition is when used to predict tropical cyclone intensity. Section 5 adapts our radar results to extract information from other satellite instruments. It is beyond this paper's scope to determine if tall convection triggers wind intensification (or vise versa) or if some third event triggers both the tall convection and wind intensification [*Craig and Gray*, 1996].

2. Data

[5] Tropical cyclone intensity is estimated every six hours in the Unisys corporation's compilation of official storm tracks from the National Hurricane Center (NHC) and Joint Typhoon Warning Center. To calculate the intensification rate, we interpolate to find the intensity six hours before and after an overflight of the Tropical Rainfall Measuring Mission (TRMM) satellite. The official intensity estimates were established without reference to TRMM Precipitation Radar observations, allowing us to test if the radar provides new information.

[6] Infrared and passive microwave data provide less precise measurements of a convective tower than does the TRMM Precipitation Radar. In the infrared, the tower itself is not visible; instead, outflowing clouds are seen expanding from the top of the tower. With 85 GHz microwave radiometers currently in Earth orbit, ice particles in a tower and in the surrounding eyewall can be detected but the data's horizontal and vertical resolution are insufficient for studying individual convective towers [*Malkus*, 1959]. In contrast, the 13.8 GHz Precipitation Radar has sufficient resolution and coverage: 250 m vertical resolution, 5 km horizontal resolution, and full coverage of the Tropics (within 35° of the Equator) [*Kozu et al.*, 2001].

[7] Precipitation Radar data show that extremely tall convective towers are fairly common in tropical cyclone eyewalls. In particular, we find that 22% of eyewalls contain at least one convective tower with an effective radar reflectivity of 20 dBZ at least 14.5 km above the ocean's surface. These towers are truly extreme—*Cecil et al.* [2002] found that only 1% of convective precipitation over ocean and 2–4% of convective precipitation in eyewalls have a 20 dBZ signal above 15 km. As a reference point, consider that the climatological height of the tropopause is 15.1 km with a 0.6 km standard deviation when the tropopause is sampled at the locations and months of the TRMM tropical cyclone overflights [*Hoinka*, 1999]. The climatological height is only a rough guide because a tropical cyclone's warm core and deep convection raises the tropopause.

[8] We look for convective towers in the 163 best Precipitation Radar overflights of tropical cyclone eyewalls during 1998 to 2003. These overflights observe all or most of the eyewall, occur over ocean, have simultaneous infrared and passive microwave observations, and see storms at tropical cyclone intensity (sustained winds $\geq$33 ms^{-1}). We

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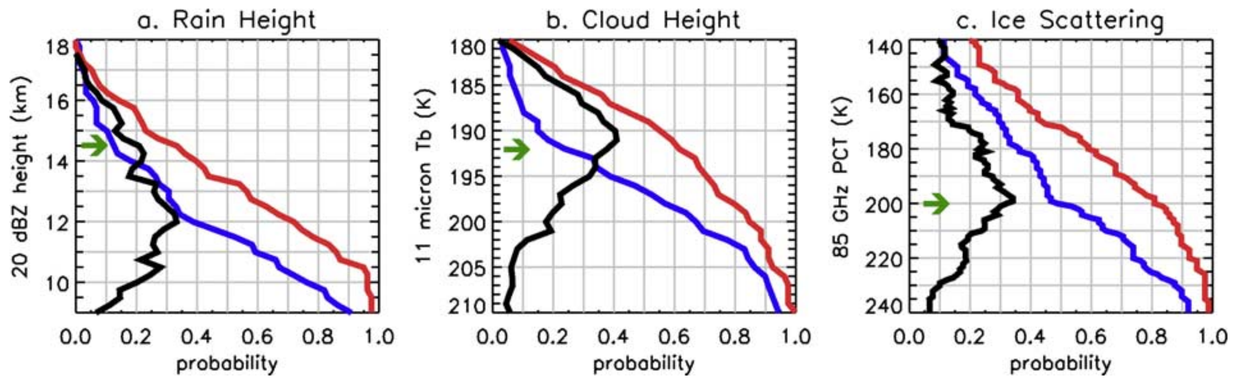

Figure 1. Cumulative Distribution Functions (CDFs) for 76 overflights of intensifying tropical cyclones (red) and 87 overflights of non-intensifying tropical cyclones (blue). Intensification is defined as an increase in intensity between six hours before and after the overflight. The black line shows the difference between the intensifying and non-intensifying CDFs. A green arrow indicates a threshold discussed in the text.

manually locate the "eyewall area" for every overflight: a donut-shaped area that contains any 100 mm/h and most of the 10 mm/h surface rain adjacent to the eye. We restrict our study to the eyewall because the 215 to 247 km wide swath of the Precipitation Radar is too narrow to regularly include all of a tropical cyclone's rain bands.

[9] To make our storm height calculation more easily adaptable to other radars, we calculate the maximum height of attenuation-corrected 20 dBZ reflectivity produced by the TRMM 2A25 algorithm [*Iguchi et al.*, 2000]. To calculate height, we multiply the distance along the line of sight by the cosine of the zenith angle where the line of sight intersects the Earth ellipsoid. We do not use the storm height calculated by the 1B21 and 2A23 algorithms, which examine the instrument noise and returned power in 250 m range gates above the storm. The 1B21/2A23 method cannot be applied to ground radars because ground radars lack 250 m vertical resolution. The two methods produce similar results: in over 90% of eyewalls we examine, the maximum 1B21/2A23 storm height is within 250 m of the maximum storm height calculated by our method.

3. Method

[10] The first goal of this section is to establish that the maximum height of convection is statistically linked to tropical cyclone intensification. Next, we define "extremely tall" convective towers in a way that takes advantage of this statistical association. Last, we use a similar approach to define "high" clouds using infrared data and "significant" ice scattering using passive microwave data.

[11] To establish that the height of convection does depend statistically on intensification, we calculate the maximum height that 20 dBZ reflectivity reaches in the eyewall of each Precipitation Radar overflight. Then, we calculate the Cumulative Distribution Function (CDF) of maximum height of each of the intensifying tropical cyclones and the corresponding CDF for the non-intensifying tropical cyclones (Figure 1a). Choose any percentile from the 5th through 95th (a probability of 0.05 to 0.95), and the intensifying tropical cyclone (red) will have an eyewall maximum height above that of the non-intensifying tropical cyclone (blue). The fact that the red line is not on top of the blue line is statistical evidence that the height of convection does depend on whether or not the tropical cyclone is intensifying.

[12] The statistical difference described above motivates us to look for a way to use convective height to help predict tropical cyclone intensity. For example, Figure 1a shows that intensifying cyclones are twice as likely as non-intensifying cyclones to have a 5 km wide Precipitation Radar pixel in their eyewall with a 20 dBZ reflectivity signal that reaches 14.5 km. A threshold less than 20 dBZ is not possible because the sensitivity limit of the Precipitation Radar is 16–18 dBZ [*Kozu et al.*, 2001]. We have also found that higher reflectivity thresholds, such as 30, 40, or 50 dBZ, are less effective than 20 dBZ for distinguishing the intensifying and non-intensifying populations. These higher reflectivity thresholds occur at lower altitudes than the 20 dBZ threshold. In other words, variation in the height of heavy precipitation (30 to 50 dBZ) at relatively low altitudes is less correlated with tropical cyclone intensification than variation in the height of light precipitation (20 dBZ) that occurs at higher altitudes.

[13] Our method for defining "high" clouds also uses a difference between intensifying and non-intensifying tropical cyclones. We examine the 11 μ infrared brightness temperature (Tb) of the TRMM Visible and Infrared Scanner (VIRS), which has a 3 km horizontal resolution [*Kummerow et al.*, 1998]. Because temperature decreases with altitude in the troposphere, we look for very cold temperatures. The black line in Figure 1b shows that intensifying eyewalls (red) have at least twice the chance of non-intensifying eyewalls (blue) of having a minimum Tb $\leq$ 192 K.

[14] To look for significant ice concentration, we examine the 85 GHz polarization-corrected brightness temperature (PCT) of the TRMM Microwave Imager (TMI). TMI's 85 GHz channel has 5 km $\times$ 7 km horizontal pixels with a 5 km $\times$ 14 km distance between pixel centers [*Kummerow et al.*, 1998]. *Spencer et al.* [1989] were the first to define PCT as 1.818Tb(V) – 0.818Tb(H). *Cecil et al.* [2002] and others use PCT $\leq$ 200 K as an indicator that a large number of ice particles are scattering the 85 GHz emission. Because the black line in Figure 1c shows that the maximum difference between the CDFs of intensifying and non-intensifying tropical cyclones occurs near 200 K, we adopt this common threshold.

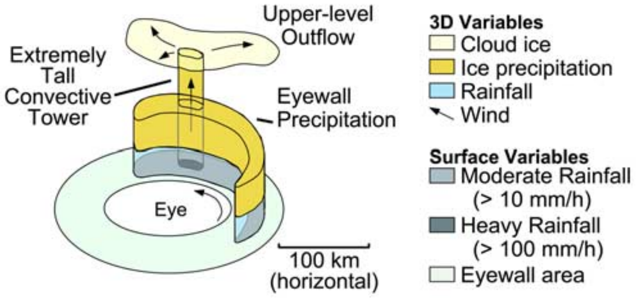

Figure 2. A schematic diagram of a tropical cyclone eyewall with an extremely tall convective tower.

[15] Lightning is more likely in eyewalls that contain an extremely tall convective tower, but we do not find an association between lightning and tropical cyclone intensification, using the TRMM Lightning Imaging Sensor.

[16] So far in this section, we have described ways that eyewalls vary, but in other ways, eyewalls are similar to each other. For example, the median height of the eyewall's precipitation remains 7.5–9 km whether or not there is an extremely tall convective tower that rises 14.5–18 km high in the eyewall. In addition, the Precipitation Radar shows that the eyewall is an arc of precipitation that usually extends less than halfway around the tropical cyclone's eye whether or not the eyewall includes an extremely tall convective tower. These properties of an eyewall are shown conceptually in Figure 2 to give the reader a sense of a convective tower's relation to the rest of the eyewall.

4. Results

[17] In the previous section, we constructed a definition of extremely tall convective towers to help predict tropical cyclone intensity change. To construct the definition, we looked at convective height conditioned on intensity change. For example, Figure 1a showed that 33% of tropical cyclones that are undergoing intensification contain at least one extremely tall convective tower pixel (20 dBZ $\geq$ 14.5 km).

[18] Now we want to measure the usefulness of our definition, so we look at intensity change conditioned on convective height. In particular, Figure 3 shows a 71% chance of tropical cyclone intensification if an extremely tall convective tower exists in the eyewall. The chance of intensification drops to 46% when the tallest convective cell is 10.0 to 14.25 km high and to only 13% when the tallest cell is less than 10.0 km high.

[19] The association of extremely tall convective towers with tropical cyclone intensification is statistically significant. A one-sided t-test on the mean wind speed change in the 35 eyewalls with an extremely tall convective tower ($m = 4.2$, $s = 6$) and the 128 eyewalls without such a tower ($m = -0.4$, $s = 4$) is significant at the 0.01 level. Both the sample mean m and standard deviation s have units of change in wind speed (ms^{-1}) within ±6 hours of the TRMM overflight.

[20] Simultaneous observations by two independent instruments reinforce these Precipitation Radar results. Twenty-nine of the 35 eyewalls with an extremely tall convective tower detected by the Precipitation Radar have both an infrared-based high cloud and significant ice scattering in the microwave.

5. Implications for Forecasters

[21] When predicting tropical cyclone intensity, forecasters must consider data availability and how far in the future they wish to predict intensity. The radar technique presented above explains 16% of the variance of intensity within ±6 hours of the radar observation. Forecasters, however, would find our radar results less useful for predicting intensity 24-hours in the future because the correlation is weaker (9% of variance explained).

[22] The TRMM Precipitation Radar typically flies over an individual tropical cyclone only once every five days, but forecasters could use our technique more often if it were adapted to aircraft or ground radars. It is difficult to adapt our technique because the vertical and horizontal resolution of aircraft and ground radars vary considerably over short distances. For example, the vertical resolution drops to 1 km when 30 km from the tail radar of a NOAA WP-3D aircraft and to approximately 3 km when 200 km from a NOAA WSR-88D ground radar [*Griffin et al.*, 1992; *Marks et al.*, 1992; *Brown et al.*, 2000]. Despite such limitations, other researchers have detected convective towers in eyewalls using aircraft or ground radar [*Heymsfield et al.*, 2001; *Malkus*, 1959]. The TRMM Precipitation Radar saw three eyewalls during 1998 to 2003 that contained extremely tall convective towers and that were within range of a WSR-88D ground radar on the United States coast. In each of these three cases, the ground radar also detected a 20 dBZ signal above 14.5 km, our definition of an extremely tall convective tower.

[23] A microwave/infrared technique would also be useful to forecasters when no data were available from the TRMM Precipitation Radar. Every time that a microwave radiometer with an ice scattering channel (such as 85 GHz) flies over a tropical cyclone, a forecaster could create a composite image similar to the right side of Figure 4, except without the radar-derived convective tower location. The image would show the 200 K PCT 85 GHz "ice" contour superimposed on the 192 K "high cloud" contour of the

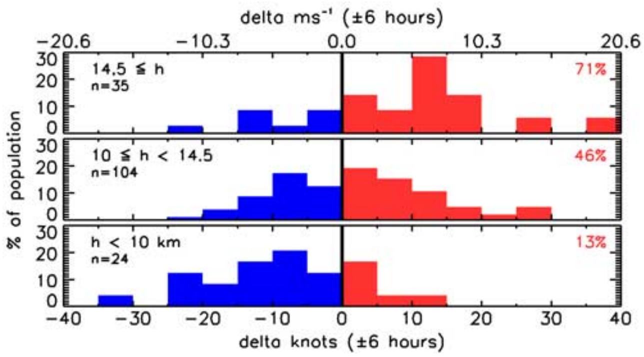

Figure 3. Tropical cyclone overflights segregated into three populations of size n based on the maximum height h of their eyewall's 20 dBZ signal. The horizontal axis is the ±6 hour change in maximum sustained surface winds. The vertical axis is the percent of the population in a 2.6 ms^{-1} bin (5 kt bin). The red numbers on the right tell the percent of overflights that were intensifying.

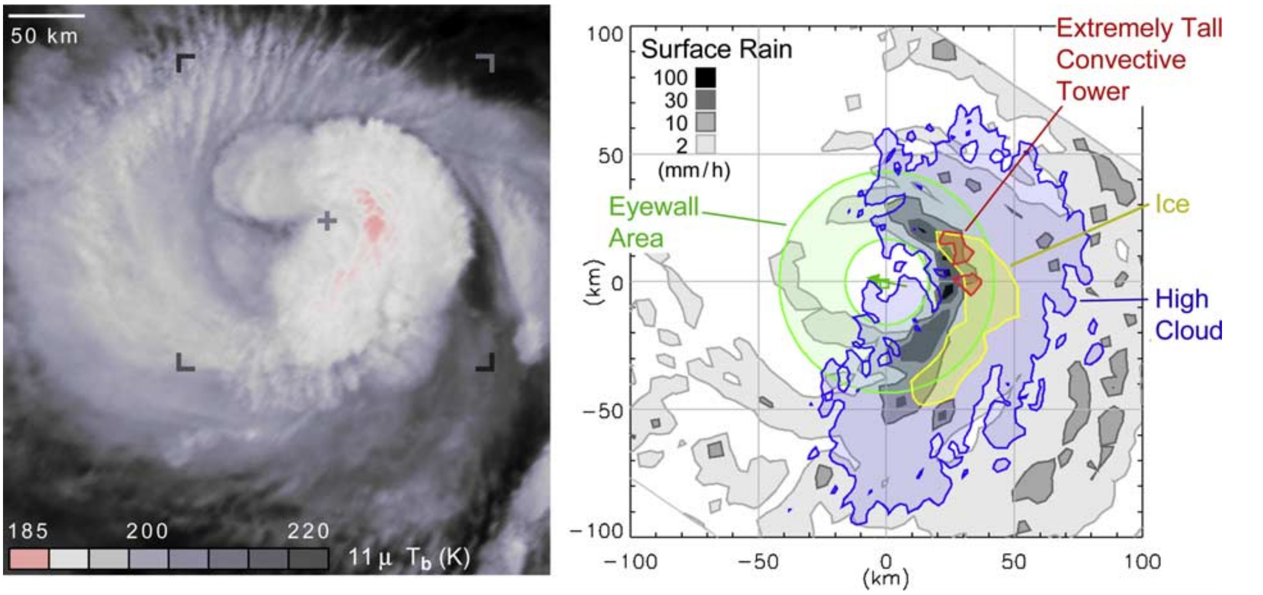

Figure 4. Hurricane Carlotta at 1055 UT on 20 June 2000, at 14.66°N, 101.02°W. The left panel shows TRMM VIRS 11 μ infrared brightness temperature (Tb). The image gives a sense of explosive expansion of upper-level outflow from the convective tower shown in pink. The four corner brackets in the left panel locate the boundary of data shown in the right panel. Based on thresholds determined from Figure 1, extremely tall convective towers are shown in red, high clouds are shown in blue, and ice scattering is shown in yellow. Interpolating the NHC best track data, the tropical cyclone's intensity was 38 ms^{-1} at the time of observation and increased by 10 ms^{-1} in ±6 hours from the time of observation.

most recent 11 μ geosynchronous infrared image. Whenever both contours occur inside the eyewall region, our TRMM analysis suggests a 73% chance that the tropical cyclone is undergoing intensification. When neither signal occurs in the eyewall, our analysis suggests a 14% chance that intensification is underway.

[24] Ultimately, intensity forecasts will improve when researchers improve mesoscale models, and our TRMM results could serve as a benchmark to help them. Models with sufficient resolution, such as the models used by *Yau et al.* [2004] and *Braun* [2002], could attempt to reproduce the association between tall convective towers and tropical cyclone intensification that we have derived from TRMM observations.

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