

Vertical Structure of Hurricane Eyewalls as Seen by the TRMM Precipitation Radar

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ABSTRACT

Statistical analysis of the vertical structure of radar echoes in the eyewalls of tropical cyclones, shown by the Tropical Rainfall Measurement Mission (TRMM) Precipitation Radar (PR), shows that the eyewall contains high reflectivities and high echo tops, with deeper and more intense but highly intermittent echo perturbations superimposed on the basic structure. The overall echo strength, height of echo top, and presence of intense echo perturbations all increase with vortex strength. Intense echo perturbations decrease in frequency with low sea surface temperatures. When the PR data are normalized by the amount of radar echo in each sample and examined quadrant by quadrant relative to the direction of the environmental shear, the nature of convective processes in different parts of the eyewall becomes apparent. The normalized statistics of the echo intensity, brightband structure, and maximum echo-top height show that processes generating convective precipitation are generally favored in the downshear-right region of the eyewall, while the nonnormalized statistics indicate that the vertical wind shear determines the placement of precipitation particles downwind of the generation zone such that the precipitation maximum occurs about one quadrant downwind of the convective generation zone. When the track speed exceeds the magnitude of the shear vector, this pattern modifies such that the asymmetry rotates one quadrant to the right. The statistics, moreover, indicate that vertical wind shear is the factor determining the placement of precipitation particles around the storm, while other factors determine the location, intensity, and means of their generation.

1. Introduction

The precipitation pattern of a tropical cyclone is characterized by one or more quasi-circular eyewalls that surround the precipitation-free eye of the storm, while farther from the storm center spiral rainbands dominate (Houze 2010). The eyewall is the zone of primary uplift within the cyclone. The basic dynamics of the eyewall are described by Emanuel (1986), and observations of eyewalls are consistent with his theory in showing that the eyewall is marked by a radar reflectivity signature that slopes radially outward with height (see, e.g., Marks and Houze 1987). Convective-scale buoyant updrafts superimposed upon the secondary circulation, intense updrafts associated with mesovortices within the eyewall, and asymmetries resulting from shear and other environmental conditions may disrupt and influence the tropical cyclone to produce

departures from the mean slantwise-neutral circulation (Emanuel 1986; Marks and Houze 1987; Black et al. 1994; Schubert et al. 1999; Black et al. 2002; Rogers et al. 2003; Braun et al. 2006). The eyewall is a precipitation feature unique among convective phenomena occurring in the tropics, and understanding its structure and evolution is key to understanding the internal dynamics of tropical cyclones as a whole.

Although the horizontal pattern of surface rain falling in the eyewall region and the variations in that pattern resulting from environmental conditions have been exhaustively studied (e.g., Rogers et al. 2003; Lonfat et al. 2004; Chen et al. 2006), relatively few studies have examined the accompanying vertical structure of the precipitation (as seen by radar) over a large sample. Marks (1985) and Dodge et al. (1999) examined the precipitation and kinematic structure of individual intense Atlantic hurricanes with airborne Doppler radars. Black et al. (1996) performed a comprehensive statistical analysis of the kinematic and precipitation structure of intense tropical cyclones, using the tail airborne Doppler radar data from seven Atlantic hurricanes. Examining the vertical

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distribution of the radar echoes in the eyewall is important because it is indicative of the microphysical and dynamical processes producing the eyewall precipitation and consequently provides insight into the vertical profiles of heating, vorticity, and potential vorticity in the eyewall.

In this study, we use data collected by the Tropical Rainfall Measurement Mission (TRMM) Precipitation Radar (PR) during the 1998–2007 Atlantic basin hurricane seasons to statistically analyze the vertical precipitation structure of the eyewalls of intense mature tropical cyclones. Using the PR, Cecil et al. (2002) found that in the convective portions of eyewalls, the vertical distribution of radar reflectivity above the melting level in some respects resembles other tropical oceanic convection. However, the eyewall echoes have more intense low-level reflectivity values and a greater vertical extent. In this study, we build on this previous work by examining the vertical distribution of PR radar echoes to better understand how the convective precipitation generation processes are distributed around the eyewall under various storm conditions and how the wind field leads to the placement of the generated precipitation particles within the eyewall rainfall pattern.

After describing our data and methods of analysis in section 2, we determine the relationship of environmental wind shear, storm intensity, sea surface temperature (SST), and storm translation to the variation of eyewall vertical structure in section 3, examine how the classified features vary from quadrant to quadrant in relation in section 4, and synthesize our results and suggest goals for future study in section 5.

2. The TRMM Precipitation Radar, CFADs, and quadrant-by-quadrant analysis

The TRMM PR is described by Kummerow et al. (1998). We use the version 6 2A25 dBZ data (TSDIS 2007) to obtain a three-dimensional view of reflectivity structure. The approximately 250-m (at nadir) resolution of the PR makes it ideal for evaluating changes in vertical structure of precipitation. The approximately 215-/247-km (pre-/postboost, with the boost occurring in August of 2001) swath width and the roughly twice daily sampling (for a given location) provide numerous overpasses of multiple tropical cyclones. The horizontal resolution is 4.3/5 km (pre-/postboost). We use contoured frequency by altitude diagrams (CFADs; Yuter and Houze 1995) to display the binned reflectivity values. CFADs are joint probability distributions that allow for the accumulation of data from numerous overpasses in a single plot while taking advantage of the PR's high resolution in the vertical. Since the focus of this study is on the vertical structure of precipitation, the change in

horizontal resolution does not affect the results significantly; however, the larger swath width provides a somewhat more complete view of an individual storm. CFADs provide insight into both the dynamics and microphysics governing the observed reflectivity features and allow for analysis of the variability of the structures seen within an individual storm as well as from one storm to another.

Our analysis includes the overpasses of all storms within the Atlantic basin between 1998 and 2007 that reached category 4 ($59\text{--}69\text{ m s}^{-1}$; Saffir 2003; 8 storms) or category 5 ($>69\text{ m s}^{-1}$; 17 storms) sometime during their lifetimes. Only overpasses of when the storm was at least category 1 ($>32\text{ m s}^{-1}$) are included. A total of 215 overpasses obtained in these storms are thus included in this study, with 66 overpasses containing data from the eyewall region. This method is useful for documenting changes in structure across the categories independent of changes occurring for an individual storm.

Following Houze et al. (2007), we remapped the PR reflectivity data onto a Cartesian grid after applying small corrections to the geolocation of the upper-level data. Cartesian gridding allows for visualization in the National Center for Atmospheric Research (NCAR) Zebra software (Corbet et al. 1994; James et al. 2000) and facilitates computation of CFADs. Reflectivity values in the Cartesian grid were counted in 1-dB bins every 0.25 km in height. Data were subdivided into convective or stratiform categories according to the TRMM version 6 2A23 product (Awaka et al. 1997; TSDIS 2007; Awaka et al. 2009). Individual CFADs are sorted into the groupings shown in Table 1, with the number of eyewall overpasses in each grouping shown in parentheses. The narrow swath width of the PR renders most individual cases at least somewhat incomplete, but a comparison between full eyewall coverage statistics (33 overpasses) and the partial coverage statistics (33 overpasses) reveal highly similar CFADs. Therefore, we combined the reflectivity distributions of all 66 overpasses into a single larger data sample.

CFADs were plotted either to indicate total counts or were normalized by the maximum frequency in the sample (Houze et al. 2007). The total-count CFADs represent the *probability* of occurrence of radar echo as a function of altitude and intensity (i.e., they emphasize the bulk amount of echo in a given portion of a storm). The CFADs for different quadrants then provide information regarding the net amount of precipitation at different locations around the eyewall. Horizontal variations of the bulk rainfall around the eye are well known to be related to variations of the dynamics of the vortex, owing to variations in shear, storm motion, or other factors affecting the vortex as a whole.

TABLE 1. Groupings of individual overpasses and the number of overpasses within each grouping.

Grouping	Total overpasses (eyewall overpasses)	Definition at time of overpass
CAT12345	204 (66)	All overpasses
CAT 12	68 (19)	$33 \leq \text{max. sustained winds} \leq 49 \text{ m s}^{-1}$
CAT45	81 (27)	$\text{Max. sustained winds} \geq 59 \text{ m s}^{-1}$
Low shear	97 (32)	$\leq 7.5 \text{ m s}^{-1} (850\text{--}200 \text{ hPa})^{-1}$
High shear	105 (33)	$> 7.5 \text{ m s}^{-1} (850\text{--}200 \text{ hPa})^{-1}$
Marginal SST	66 (25)	$26^\circ \leq \text{SST} \leq 28^\circ\text{C}$
High SST	133 (41)	$> 28^\circ$
Low track speed	77 (24)	$< 5 \text{ m s}^{-1}$
High track speed	125 (42)	$\geq 5 \text{ m s}^{-1}$

In contrast, the normalized CFADs represent a conditional probability obtained by normalizing by that varying amount of precipitation. This approach was used by Houze et al. (2007). Dividing all the bins by the maximum frequency in the distribution removes the effect of the bulk amount of radar echo in a given subset of the data, such as all the data representing a quadrant or other subregion of the storm. However, this normalization technique has an additional advantage. Stratiform precipitation, usually widespread and horizontally uniform, has a frequency distribution that concentrates most of the frequencies into few reflectivity bins, resulting in a highly uniform and peaked profile. Convective precipitation, in contrast, has echoes that tend to have a more variable distribution because the higher reflectivities are concentrated in small cores that are surrounded by lower reflectivities. The bins in these more variable distributions, even the peaks, thus tend to have significantly lower frequencies than their stratiform counterparts. Normalizing by the maximum frequency brings the maxima in the profile to the same magnitude, allowing every profile to be plotted on the same scale. This normalization technique thus allows for direct comparisons between different regions as well as different *types* of precipitation.

The normalized CFADs for storm quadrants emphasize the variation of the vertical structure of radar echoes between different sectors of the storm. These differences are, in turn, related to differences in convective-scale dynamics and microphysics from one quadrant to another. Other subsets of the data, such as all storms reaching a certain intensity category, storm motion, environment shear, and SST can be similarly normalized. We use the CFADs for these subsets to indicate how these factors influence the vertical structure of the precipitation, and by implication how these factors affect the dynamical and microphysical nature of the convective processes in the eyewall.

This study uses the storm center, intensity, track direction, storm translation speed, and eye diameter from

the National Hurricane Center (NHC) best-track data (<http://www.nhc.noaa.gov/pastall.shtml#hurdat>). SST data are from the National Oceanic and Atmospheric Administration (NOAA) Comprehensive Large Array Data Stewardship System (CLASS) gridded at 50-km-resolution global SST, generated twice weekly from 8-km global infrared satellite SST observations and averaged within a 3° radius from the storm center. We estimate conditions and storm position at TRMM overpass times via simple interpolation between observations bracketing the time of overpass. The overpass samples are referred to by the status of the storm *at the time of the overpass*. In cases lacking a report of eye diameter, it is subjectively determined from storm-center information and data from the TRMM Microwave Imager (TMI; Kummerow et al. 1998) and the PR data (when available). All of the overpasses included in this study have the storm center contained within the TMI's swath width (760 km preboost, 878 km postboost). TMI data from 37- and 85-GHz channels are used in combination since 37 GHz is more sensitive to lower-level rain and can thus see closer to the portion of the eyewall close to the surface, but has a lower spatial resolution than the 85-GHz channel, which is more sensitive to ice (Lee et al. 2002). This methodology assumes a contiguous circular eyewall. In the case of an eyewall with broken echo coverage, estimates of the eye diameter are made on the feature exhibiting the geometry of the arc of a circle or ellipse. For an elliptical eyewall, the long and short axis average is used to define eyewall. The storm center from the best-track data is visually checked against the PR and TMI data, since the circulation center of the storm often does not necessarily match the center of the precipitation feature (Bluestein and Marks 1987). If necessary, the center of the analysis is manually shifted to better align with the precipitation features.

Unlike previous works that subjectively parsed the data into categories based on particular features, such as defining an area as "eyewall," "rainband," "stratiform," etc. (e.g., Black et al. 1996; Cecil et al. 2002), this study

uses an objective method to sort the data into annuli based on radius from the storm center. The storm-center and eye-diameter reports establish the eye radius R_e , which marks the inner boundary for the eyewall region 1. The outer boundary of the first annulus R_1 assumes a 45° slope of the eyewall (Marks and Houze 1987) with flow up to a tropopause height of 17 km (Jordan 1958), defining R_1 as $R_1 = R_e + 17$ km. This constant eyewall width was selected to provide the best chance of capturing the full sloping eyewall and the precipitation directly underneath. Subsequent annuli are defined by their outer boundaries, which are multiples of R_1 , such that $R_2 = 2R_1$, $R_3 = 3R_1$, and so on, up to region 10, which is defined as everything outside of region 9 that is within the cropped overpass (typically 1000 km from end to end). This study focuses on region 1, which is the region between R_e and R_1 . Subsequent studies will examine other regions of the storm.

This study also utilizes a quadrant-by-quadrant analysis to study different features around the eyewall. The quadrants are oriented by the 850–200-hPa shear vector, calculated from the National Centers for Environmental Prediction (NCEP) reanalysis zonal u and meridional v winds. The 200-hPa wind vectors were subtracted from the 850-hPa wind vectors at every point within a ring of wind data 500–750 km from the storm center to avoid the influence of the storm's circulation. These individual shear vectors were then averaged to create the mean shear vector and interpolated (using the interpolation method described above) to estimate the shear at the time of the overpass. This calculation was also performed for a ring 200–800 km from the storm center as was done in Chen et al. (2006), and our results are strongly consistent with theirs. However, the larger distance was used to eliminate, as much as possible, the influence of the storm's wind field. The quadrants are defined counter-clockwise from the direction of this mean shear vector. An example of this method is illustrated in Fig. 1, highlighting the annuli and quadrants on an overpass of Hurricane Katrina on 28 August 2005. Region 1 is bounded in blue and purple, indicating that this particular overpass contributes data from the upshear quadrants.

3. The general eyewall structure

Often, for simplicity, the eyewall is thought of as a uniform ring of intense radar reflectivity. It is well known, however, that the eyewall cloud is seldom perfectly uniform or symmetric. In this section, we emphasize bulk variations in the eyewall strength without regard to storm asymmetry. In section 4, we will investigate factors associated with the asymmetric structure of the storm.

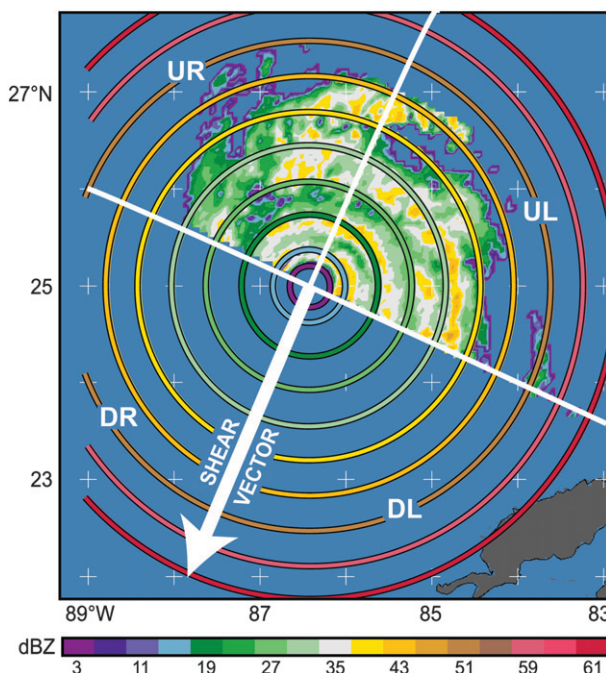


FIG. 1. TRMM PR overpass of Hurricane Katrina (2005). Data are plotted at 2.5-km altitude. The color-filled contours indicate reflectivity (dBZ). The annuli are bounded by the colored rings, with region 1 bounded by purple and blue rings. The entire area outside of the last red ring is considered region 10. Quadrants are indicated in white (UL is upshear left, UR upshear right, DR downshear right, and DL downshear left). Shear vector is indicated by the white arrow.

a. Basic eyewall vertical structure

To characterize the basic vertical structure of the eyewall, we compare its radar reflectivity CFAD (region 1 in Fig. 1) with that of the more ordinary tropical convection, which, as pointed out by Houze (2010), occurs in the distant outer region of the storm (region 10). Figure 2a contains the normalized total accumulation CFAD for all eyewall overpasses [i.e., categories 1–5 (CAT12345)]. Figure 2b shows the corresponding CFAD for the outer region. The bulk of the distribution contained within the contours for frequencies greater than 50% of the maximum frequency in the distribution (shading from yellow to red) is referred to below as the *modal distribution*. We refer to the frequencies that are less than 50% of the maximum frequency (green, teal, and blue contours) as the *outlier distribution*.

Below 5 km, in the eyewall region (Fig. 2a), the modal distribution falls in the range of 22 to approximately 43 dBZ and its peak value is centered at about 30 dBZ. These are comparable to the values seen in Marks (1985) and Dodge et al. (1999), which both exhibited high reflectivity (40+ dBZ) cores in the eyewall below 5 km, accompanied by a sharp gradient on the inner

edge, with a less steep gradient on the outward edge. The eyewall modal distribution below 5 km is more intense than the modal distribution at these same altitudes in the total accumulation CFAD for the outer region precipitation of region 10 (Fig. 2b, smoother because of the larger amount of data), which ranges from 18 to 35 dBZ and has a much flatter distribution that is mostly concentrated below 30 dBZ.

Above 5 km, the reflectivities in the modal distribution of the eyewall seen in Fig. 2a sharply decrease to being centered at approximately 22 dBZ above 5 km and reaching to approximately 9 km, with a width of about 6 dB. These results are consistent with the mean reflectivity profiles seen in Black et al. (1996), who show high reflectivity in the eyewall varying between 32 and 37 dBZ, dropping to 22 dBZ at 10 km. In the outer region (Fig. 2b), the upper modal distribution is centered at a lower reflectivity (~ 20 dBZ) and reaches only about 8 km altitude.

The outlier distributions of the eyewall and outer distributions also differ. The eyewall outliers seen in Fig. 2a reach values well over 40 dBZ and extend to 50+ dBZ, significantly more intense than the 35–45 dBZ seen in the outer region outliers (Fig. 2b). Above 5 km in the eyewall, 20-dBZ outlier echoes reach heights exceeding 12 km. These outliers indicate the presence of intermittent but very intense convective perturbation embedded within the eyewall, likely the localized buoyant convective cores noted in numerous aircraft and modeling studies (Jorgensen et al. 1985; Marks and Houze 1987; Black and Hallett 1999; Braun et al. 2006).

The distant outer-region convection (Fig. 2b) would be expected to contain a mix of active intermittent buoyant convective cells and older stratiform precipitation (Houze 1997), whereas the eyewall precipitation (represented in Fig. 2a) is not simply ordinary buoyant convection but results in large part from the concentrated sloping updraft that constitutes the secondary circulation of the vortex (Emanuel 1986). The comparisons of the CFADs in Figs. 2a and 2b indicate that the eyewall type of convection is capable of attaining both greater heights and greater intensities than convection in the outer region. Cecil et al. (2002) found similar differences between the eyewall and oceanic convection outside of a hurricane environment.

b. Convective versus stratiform echo in the eyewall and outer region

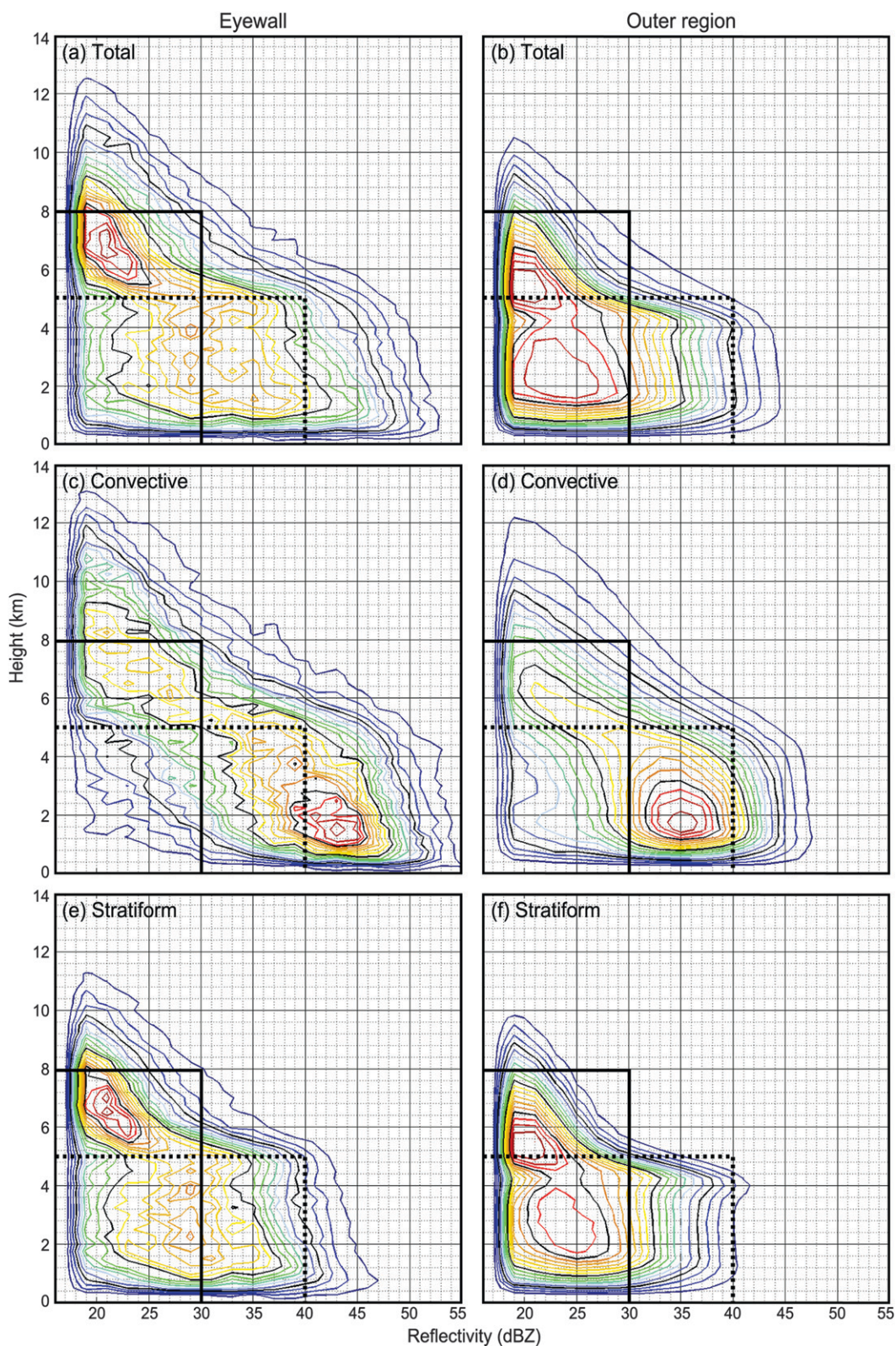
The TRMM PR convective/stratiform algorithm (TRMM product 2A23) classifies the more intense echoes in the eyewall as “convective” and the rest of the eyewall reflectivities as “stratiform.” This algorithm (Awaka et al. 1997) was not designed with hurricane

convection in mind, so its usefulness in the hurricane context may be limited. Nevertheless, it is interesting to examine the eyewall CFADs separated into the TRMM algorithm’s convective and stratiform components (Figs. 2c,e).

Figure 2c shows the normalized distribution for the convective-classified points within the eyewall, and Fig. 2e is the corresponding distribution for the stratiform-classified points in the eyewall. Below 4 km, the convective CFAD in Fig. 2c has a near absence of low reflectivities (<25 dBZ) and intense low-level echoes that drop off slowly in reflectivity with increasing height to 4.5–5 km. Above 5 km, the reflectivities decrease more gradually and with more variability than is seen in the stratiform-classified echo (Fig. 2e). Intense outliers occur at all levels in the eyewall convective CFAD, with reflectivities as high as 55 dBZ and heights as high as 13 km (Fig. 2c). The eyewall stratiform CFAD, in contrast to the convective CFAD, indicates a frequent occurrence of weak reflectivities below 4 km (Fig. 2e). The stratiform low-level distribution also shows a weak peak centered at 30 dBZ, as well as a distinctive bright-band signature between 4.5 and 5 km. Above that level, the reflectivities decrease sharply in height to a peak centered at 21 dBZ, with most of the distribution packed more tightly toward the modal distribution than that seen in the convective CFAD (Fig. 2c).

The convective CFADs for both the eyewall and the outer region are generally similar (Figs. 2c,d), but the echo intensities differ substantially. In the eyewall region, the entire convective low-level distribution (Fig. 2c) is shifted toward more intense values, at 5 dB or more compared to the outer region (Fig. 2d). More intense reflectivities are seen at higher altitudes above the melting level in the eyewall convective CFAD, with the modal distribution reaching approximately 9.5 km in the eyewall versus approximately 7.5 km in the outer region. The higher low-level reflectivities and stronger reflectivities at higher heights in the eyewall CFADs suggest that larger amounts of water are being transported upward and to much greater heights in eyewall convection. The eyewall and outer region stratiform profiles are also similarly shaped, although the echoes in the eyewall CFAD (Fig. 2e) are generally stronger and deeper than those in the outer region CFAD (Fig. 2f). These similarities exist despite the fact (noted above) that the stratiform precipitation mechanisms are likely different in the eyewall and outer region convection.

For the CAT12345 grouping, convective points were 41% of the total pixel count, with stratiform points being 57% (the remaining 2% are unclassified; see Fig. 2 caption). The contributions of the convective and stratiform distributions to the overall statistics are substantial. Thus,



the differences between the eyewall convective- and stratiform-classified echoes are useful for determining changes in the convective processes around the eyewall, which will be addressed in section 4.

c. Whole storm eyewall CFADs according to storm intensity

We find that hurricane intensity is the largest determinant of the intensity of the overall eyewall precipitation. Figures 3a and 3b compare CFADs for overpasses of storms of categories 1–2 (CAT12; wind speeds 33–49 m s^{-1} ; Fig. 3a) to the same storms when they reached categories 4–5 (CAT45; wind speeds $> 58 \text{ m s}^{-1}$; Fig. 3b). Three things are apparent in the modal distributions: 1) CAT12 storms have much lower reflectivities at low levels (~ 22 – 37 dBZ , peak of 29 dBZ) than CAT45 storms (~ 26 – 46 dBZ , peak of 35 dBZ); 2) the bright band in the CAT12 storms is more distinct than in CAT45; and 3) CAT45 echoes are taller at 20 dBZ ($\sim 9.5 \text{ km}$) than the CAT12 storms ($\sim 8.5 \text{ km}$). Category 3 (CAT3; not shown) storms displayed intermediate characteristics that were between these extremes. These observations are consistent with the CAT45 eyewalls having more vigorous circulations; more intense reflectivities in both the mode and the outliers are consistent with the stronger circulation supporting larger and/or more numerous particles. The more distinct bright band in CAT12 storms indicates a significant presence of melting ice. However, the fact that the CAT45 reflectivity at 5 km is not only about 5 dB stronger but also continues to increase steadily in reflectivity as the particles get closer to the surface suggests that growth by collection is made possible by the organized eyewall updraft at low levels. It is straightforward to conclude from these data that CAT12 storms are qualitatively similar to their CAT45 counterparts but weaker and therefore vertically limited, suggesting in turn that the precipitation processes increase and decrease in concert with the secondary circulation of the hurricane vortex. These fluctuations are in concert with that seen in Marks (1985) and other case studies.

The difference between the CAT12 and CAT45 storms becomes even more striking in the outlier distribution. In low levels, the CAT12 distribution extends from about 40 to about 50 dBZ ; the CAT45 distribution, on the other hand, stretches from about 46 to about 54 dBZ . The outliers are more intense in CAT45 storms at all levels (e.g., 20 dBZ at 12.5 km). CAT12 20-dBZ echoes only reach approximately 11 km . These values and the greater deviation of the outliers from the modal intensity suggest that the conditions within the stronger eyewalls are more favorable for the formation of strong intermittent buoyant updrafts superimposed on the vortex secondary circulation (Braun 2002; Marks et al. 2008; Houze 2010). By contrast, the outliers of the CAT12 distribution do not appear to stray too far from the overall structure suggested by the modal distribution.

These outcomes might seem obvious given that the intensity categories express the strength of the storm vortex, which is directly linked to the strength of the secondary circulation producing the eyewall. However, the eyewall is subject to environmental factors such as shear, SST, and storm translation. Despite external factors, the precipitation structure of the eyewall appears to have a typical vertical structure that changes little in a statistical sense except in relation to vortex strength. This stable structure is likely inherent to processes within the vortex rather than being easily influenced by changes in the environment. However, in the sample considered here, this stability of structure may partly be due to these storms being especially intense for a considerable part of their lifetime.

d. Whole storm eyewall CFADs according to sea surface temperature

Sea surface temperature is well known to limit the intensity of tropical cyclones. Gray (1968) found that largely owing to buoyancy restrictions, tropical cyclones do not tend to form in regions with $\text{SST} < 26^\circ\text{C}$. DeMaria and Kaplan (1994) showed that the maximum potential intensity of cyclones rapidly increases from 26° to 28°C and

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FIG. 2. CFADs of TRMM PR reflectivity data for all of the 1998–2007 overpasses of storms that ultimately reached category 4 or 5 intensity (the CAT12345 grouping in Table 1), for the total points of (a) region 1 (110 542 pixels) and (b) region 10 (2 637 249 pixels); for the convective-only reflectivity points of (c) region 1 (44 976 pixels) and (d) region 10 (641 828 pixels); and for the stratiform-only reflectivity points of (e) region 1 (62 527 pixels) and (f) region 10 (1 798 542 pixels). Contours represent the frequency of occurrence relative to the maximum absolute frequency in the data sample represented in the CFAD, contoured every 5%. Altitudes are geopotential height (km MSL) relative to the ellipsoidal surface of the earth. The ordinate of the CFAD is altitude (250-m increments, or bins) and the abscissa is reflectivity (dBZ; 1-dB bins). The 8-km and 30-dBZ levels are indicated by the black solid lines, and the 5-km and 40-dBZ levels are indicated by the black dotted lines for ease of reference. The 20%, 50%, and 80% contours are in black for reference.

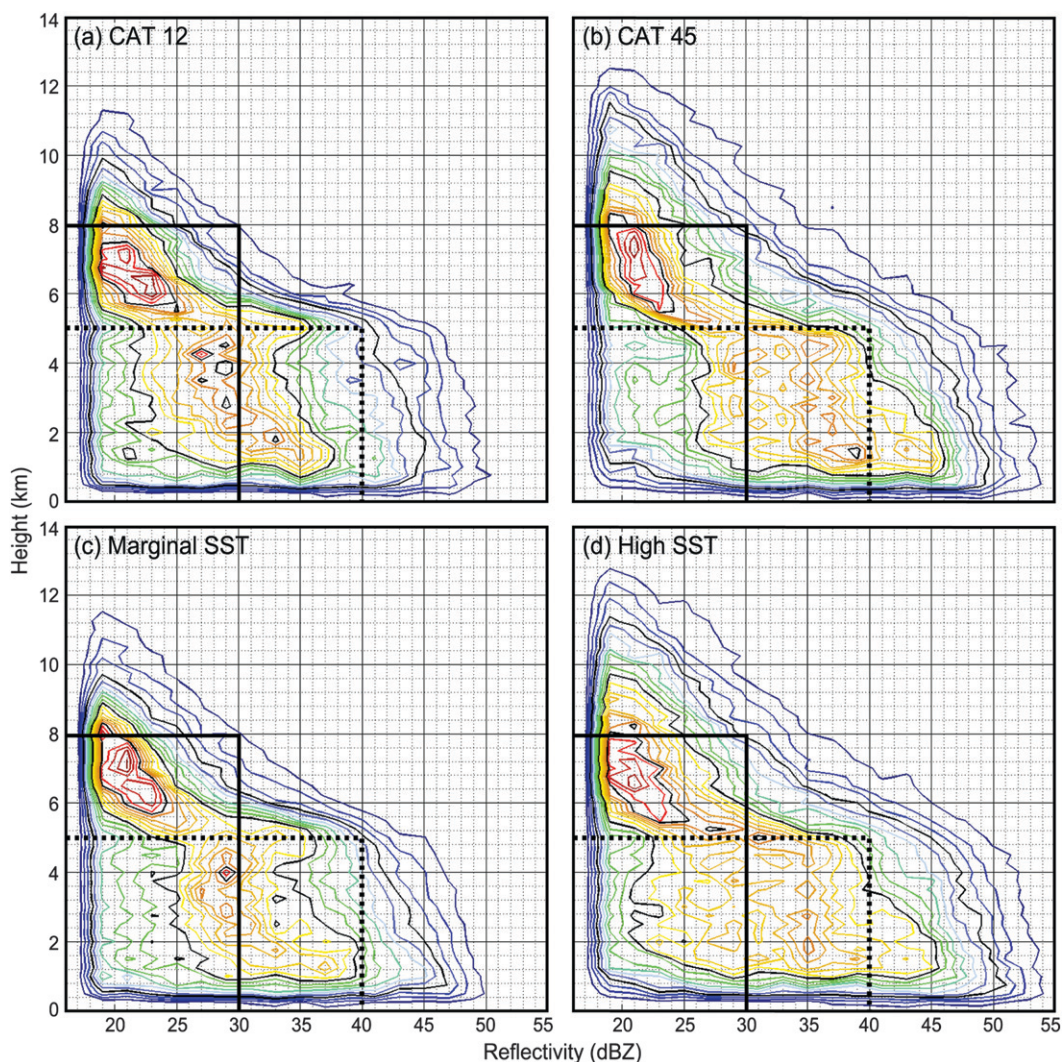


FIG. 3. Region 1 CFADs for the overpasses (a) when the storms are categories 1–2 (the CAT12 grouping in Table 1) in intensity, (b) when the storms are category 4–5 (the CAT45 grouping in Table 1) in intensity, (c) when the SST is marginal (26° – 28°C ; marginal SST grouping in Table 1), and (d) when the SST is high ($>28^{\circ}\text{C}$; high-SST grouping in Table 1). The pixel count for each grouping is the total of the quadrant listings in Table 3. Contours represent the frequency of occurrence relative to the maximum absolute frequency, contoured every 5%. Other details are as in Fig. 2.

that this rapid change levels off at approximately 28°C , possibly because of a lack of sensitivity of the tropopause to SST. However, mature tropical cyclones that travel over colder waters—either their own wake or cooler oceans—typically lose intensity, yet can sometimes hold together for relatively long periods of time (Beven et al. 2008). Thus, we are motivated to determine how SST affects the structure of the hurricane eyewall, both in terms of its mean circulation and its superimposed buoyant perturbations.

Based on the thresholds described above, we divide the overpasses into three categories: low ($\text{SST} < 26^{\circ}\text{C}$), marginal ($26^{\circ} \leq \text{SST} \leq 28^{\circ}\text{C}$), and high ($\text{SST} > 28^{\circ}\text{C}$).

The sample size for low-SST cases was small (five) and not further examined. CFADs in Figs. 3c and 3d compare the total eyewall CFADs for marginal and high SST. Below 5 km, the high-SST modal distribution has a broad peak between 30 and 35 dBZ and frequencies extending from about 21 to about 45 dBZ. The marginal SST distribution ranges from 25 to 40 dBZ (at the lowest levels, this drops to 35 dBZ by 4 km) and peaks at about 30 dBZ. The marginal case CFAD also shows a brightband signature in its modal distribution at 5 km, which is not evident in the high-SST cases. Above 5 km, both the marginal and high-SST CFAD modal values drop rapidly to center around 20 dBZ at 8 km.

The 20-dBZ echo reaches 9.5 km in the high-SST cases compared to 8.5 km in the marginal SST cases. This difference in height may be associated with a change in tropopause temperature between SSTs of 26° and 29°C as suggested by DeMaria and Kaplan (1994).

The modal distributions for both of these profiles lie somewhere between the minimum of the CAT12 storms and the maximum of the CAT45 storms. Eight of the 25 marginal SST overpasses are also CAT12 (8 of 19 CAT12 overpasses are also marginal SST), which suggests that intensity is not a dominant factor in the marginal SST distribution. Twenty of the 41 high-SST overpasses are CAT45, but 20 of the 27 CAT45 overpasses are high SST. These results suggest that high SST, and not high vortex intensity, is necessary to make high reflectivities possible. However, a strong vortex is necessary for the distribution to be *uniformly* intense in reflectivity. Lower SSTs seem to reduce the probability of having higher reflectivities but do not necessarily shift the distribution into lower reflectivities. A weaker vortex circulation (CAT12) seems to be a necessary factor in shifting the bulk of the modal distribution to lower values.

Large differences are evident in the outliers of the CFADs in Figs. 3c and 3d, with the high-SST extremes being more intense at all heights compared to the marginal SST cases. This result indicates that intermittent, very intense, very deep echoes superimposed on the eyewall are more frequent in the high-SST cases than in the marginal-SST cases. Since these infrequent but deep and intense echoes are likely the result of buoyant convective towers superimposed on the eyewall structure (Braun 2002; Houze 2010), warmer waters would be expected to better support their presence than would the cooler SSTs of the marginal-SST cases.

The CFADs suggest that cooler SST effectively shuts off the contributions of these intermittent buoyant updrafts. Since these updrafts likely contribute vorticity to the eyewall as well as provide a mechanism for mixing between the eye and eyewall (Schubert et al. 1999; Braun et al. 2006; Bell and Montgomery 2008), these results may have implications for eyewall intensification. However, the snapshot nature of this study does not allow us to delve into this aspect further.

4. Asymmetric vertical structure of the eyewall

The eyewall has an asymmetric structure resulting from the cyclone's interaction with environmental wind shear, which, although it can vary, is seldom if ever completely absent. It is therefore instructive to perform a quadrant-by-quadrant analysis of the eyewall vertical structure, where the quadrants are oriented according to

the direction of the environmental shear vector. This analysis shows how remarkably resilient the shear-induced asymmetry is to changes of storm intensity and other environmental factors. We will see that only the storm's translation alters the basic asymmetry determined by the shear. The analysis further shows how the vertical structure of the radar echoes in each quadrant responds to the various factors influencing the storm dynamics.

a. Vertical wind shear and convective processes within the eyewall

1) BULK STORM STRUCTURE

Figure 4 contains the CFADs of the eyewall for all of the overpasses (CAT12345) divided into quadrants oriented around the shear vector. The length of the shear and track vectors in this and all subsequent quadrant-by-quadrant figures are sized relative to values given in Table 2. The CFADs in this figure are not normalized but rather show total reflectivity pixel counts. The downshear-left (DL) quadrant has the largest numbers, with by far the highest concentration of larger (30–40 dBZ) reflectivity values in low levels than the other quadrants. The lower concentration of reflectivity values in the upshear-right (UR) quadrant indicates a tendency for a less full reflectivity field in this portion of the eyewall. A progression occurs around the eyewall in the low-level distribution: the downshear-right (DR) quadrant peaks at about 30 dBZ, the DL quadrant at about 35 dBZ, the upshear-left (UL) quadrant at about 29 dBZ, and the UR quadrant lacks any sort of distinctive peak at low levels. These observations suggest that the eyewall has a higher probability of having a full and intense reflectivity field, and thus precipitation, in the DL quadrant of the eyewall. The UR quadrant has a tendency to be the weakest portion of the eyewall, but it has significant variability, suggesting a possible sensitivity to either environmental or internal conditions. The DR and UL quadrants appear to be transitional quadrants. The DR quadrant has a notable lack of low reflectivities at low levels, indicating that this is a region that tends to be occupied by strong cores of reflectivity and relatively little lighter rain.

This pattern likely results from the average shear, which had a magnitude of 8.5 m s^{-1} ($850\text{--}200 \text{ hPa}$) $^{-1}$ (Table 2), a relatively modest shear value but strong enough to generate an asymmetry. Shear speeds less than 5 m s^{-1} ($850\text{--}200 \text{ hPa}$) $^{-1}$ seem to be needed to allow for symmetric convection around the eyewall (Black et al. 2002; Chen et al. 2006); at these lower shears, other factors such as the track speed can begin to influence asymmetries in the precipitation distribution (Chen et al. 2006). Table 3

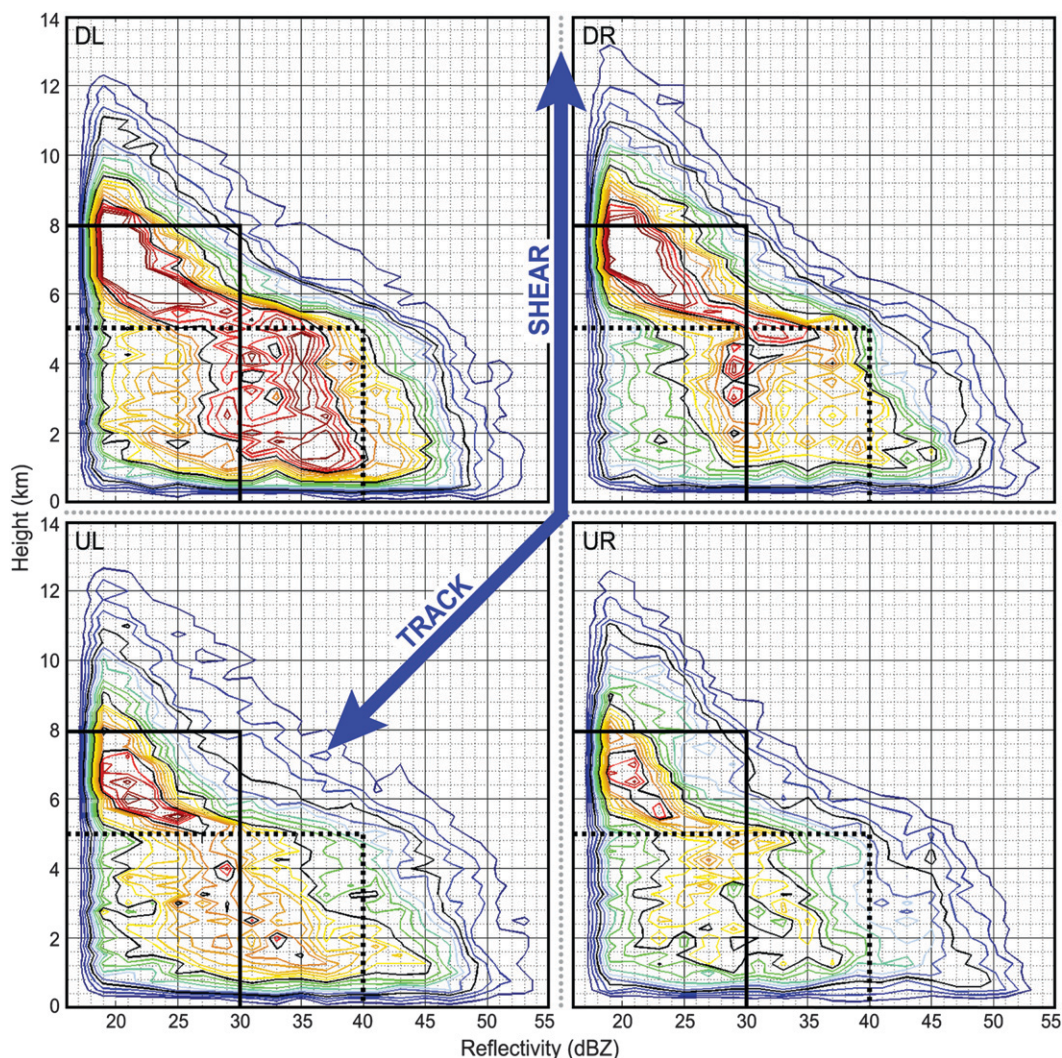


FIG. 4. Region 1 CFADs of TRMM PR reflectivity data for all of the 1998–2007 overpasses of storms that ultimately reached category 4 or 5 intensity (the CAT12345 grouping in Table 1), arranged by quadrants oriented to the average shear vector. Quadrants are labeled DL, DR, UL, and UR as in Fig. 1. The pixel count for each quadrant is listed in Table 3. The lengths and separation angle for the track and shear vectors are relative to the magnitude listed in Table 2. Contours represent the frequency of occurrence, contoured at every six points. The black contours are at 24, 60, and 96 points, respectively. Other details are as in Fig. 2.

lists the total reflectivity pixel counts for the quadrants for the different groupings of storms. Table 2 indicates that in all of the groupings the average shear is greater than 5 m s^{-1} ($850\text{--}200 \text{ hPa})^{-1}$ (the low-shear grouping's average magnitude is 5.1), and the respective reflectivity counts in Table 3 indicate the DL asymmetry. The CAT45, low-shear, high-SST, and high-track-speed groupings share a characteristic that the DR and UL quadrants are very similar in value (<500 pixel difference), whereas the other categories have a DR that has a greater number of pixels. These four groupings also share the characteristic that their average shear magnitude and average track speed are the closest in value. We

will see in the next section how this similarity in shear and track magnitude may lead to a shift in the precipitation generation within the eyewall.

2) PRECIPITATION STRUCTURE

Now that we have established where precipitation is most likely to occur (probability), we examine the likely structure of that precipitation when it occurs in a given quadrant of the storm (conditional probability). That is, we seek to understand whether and to what degree the convective mechanisms vary from one quadrant of the storm to another. Figure 5 is the same view as Fig. 4, but the CFADs in this figure have been normalized by

TABLE 2. The average of the magnitudes of the 850–200-hPa wind shear and track vectors, and difference of direction between the average shear and average track vector for each grouping. The 200-hPa wind vectors were subtracted from the 850-hPa wind vectors at every point within a ring of wind data 500–750 km from the storm center, then averaged to create the mean shear vector and interpolated to estimate the shear at the time of the overpass.

Groupings	Avg. shear magnitude [m s^{-1} (850–200 hPa) $^{-1}$]	Avg. track magnitude (m s^{-1})	Directional difference between track and shear ($^{\circ}$)
CAT12345	8.5	5.9	136
CAT12	9.9	6.2	129
CAT45	7.2	5.7	148
Low shear	5.1	5.7	177
High shear	11.7	6.1	109
Marginal SST	10.3	5.6	100
High SST	7.2	5.6	162
Low track speed	8.0	3.7	148
High track speed	8.7	7.2	130

their maximum frequency, which allows for structural differences of the nature of the radar echoes between the quadrants to be more easily seen, especially in the upper levels.

It should be noted first that all of the quadrants shown in Fig. 5 exhibit brightband enhancement near 5 km and a concentration of reflectivities near 29 dBZ, which likely results from large amounts of ice particles circulating around the eyewall region. Superimposed upon this background, the DR- and DL-quadrant CFADs (Fig. 5) exhibit more convective structures, and the convection becomes progressively weaker with more stratiform-like properties (sharp reduction in reflectivity above the melting level, echo enhancement at the melting level, weaker but uniform below the melting level) in the upshear quadrants. The DR quadrant of Fig. 5 shows the lowest probability of low reflectivity at low levels. This relative absence of low reflectivity at low levels resembles the purely convective CFAD of Fig. 2c. Comparison of Fig. 2a and the DR panel of Fig. 5 thus suggests that the most purely convective structure occurs in the DR quadrant. Ice particles sheared off of this convection likely fall out in the DL quadrant, where the probability of both lower and higher reflectivities is greater than in DR. Comparison of the DR and DL panels of Fig. 5 thus indicates that the convection in the DL quadrant is a more complete mixture of mature intense convection and associated stratiform blowoff. The DL distribution is more a combination of the convective- and stratiform-only distributions seen in Figs. 2c and 2e. The convection in the DR quadrant in comparison to that in the DL quadrant tends not to have reached full intensity yet nor to have produced much stratiform precipitation in its immediate vicinity.

TABLE 3. The number of reflectivity pixels > 18 dBZ counted within each shear-oriented quadrant of each grouping.

Category	DR	DL	UL	UR
CAT12345	28 238	34 007	26 785	21 512
CAT12	9027	10 911	6665	4696
CAT45	12 248	14 066	12 239	10 376
Low shear	12 918	14 518	12 598	12 428
High shear	15 320	19 489	14 187	9084
Marginal SST	11 593	16 071	9999	6070
High SST	16 645	17 936	16 786	15 442
Low track speed	12 565	14 336	10 687	9509
High track speed	15 673	19 671	16 098	12 003

Below 5 km in the DR quadrant, the modal distribution has a narrower distribution, with values ranging from 26 to 40 dBZ and peaking at 30 dBZ. Above the melting level, the distribution in the DR quadrant broadens into more intense reflectivities above 6 km, indicating a wider variety of particle types and sizes, as is expected in convective echo zones. This upper-level distribution narrows, but the lower-level distribution broadens significantly (22–44 dBZ) in the DL region. These features of the DL region's distribution further indicate that the DR quadrant is in an earlier stage of convective development than the DL region, the latter having a more mature mixture of stratiform echo with intense convective echo. The distribution weakens in reflectivity values overall in the UL before losing coherent low-level structure in the UR. The outliers in the CFADs also show a systematic progression around the eyewall: for the 30%–50% outliers (shown in green and teal), the low-level reflectivities begin at 45 dBZ in the lowest 2 km of the DR quadrant. The 45-dBZ contour extends upward to about 3.5 km in the DL quadrant and then shortens back down to the lowest 2 km before decreasing closer to 40 dBZ in the UR.

Comparison of the modal and outlier distributions in Figs. 4 and 5 generally supports the idea that in a sheared environment the eyewall convective updrafts form in the DR quadrant, mature and deposit most of their rainfall in the DL quadrant, and die out in the UR quadrant (Black et al. 2002). The normalized CFADs (Fig. 5) show characteristics of younger convective eyewall precipitation in the DR quadrant (broad upper-level distribution, narrower and weaker low-level distribution) that matures in the DL (narrower upper-level distribution, broad low-level distribution), then gaining progressively more stratiform-like echo properties azimuthally downwind, similar to the process discussed by Marks and Houze (1987). The nonnormalized CFADs (Fig. 4) show the most rainfall just downwind of the convective initiation zone in the DL quadrant, similar to the rainfall asymmetry seen in Chen et al. (2006).

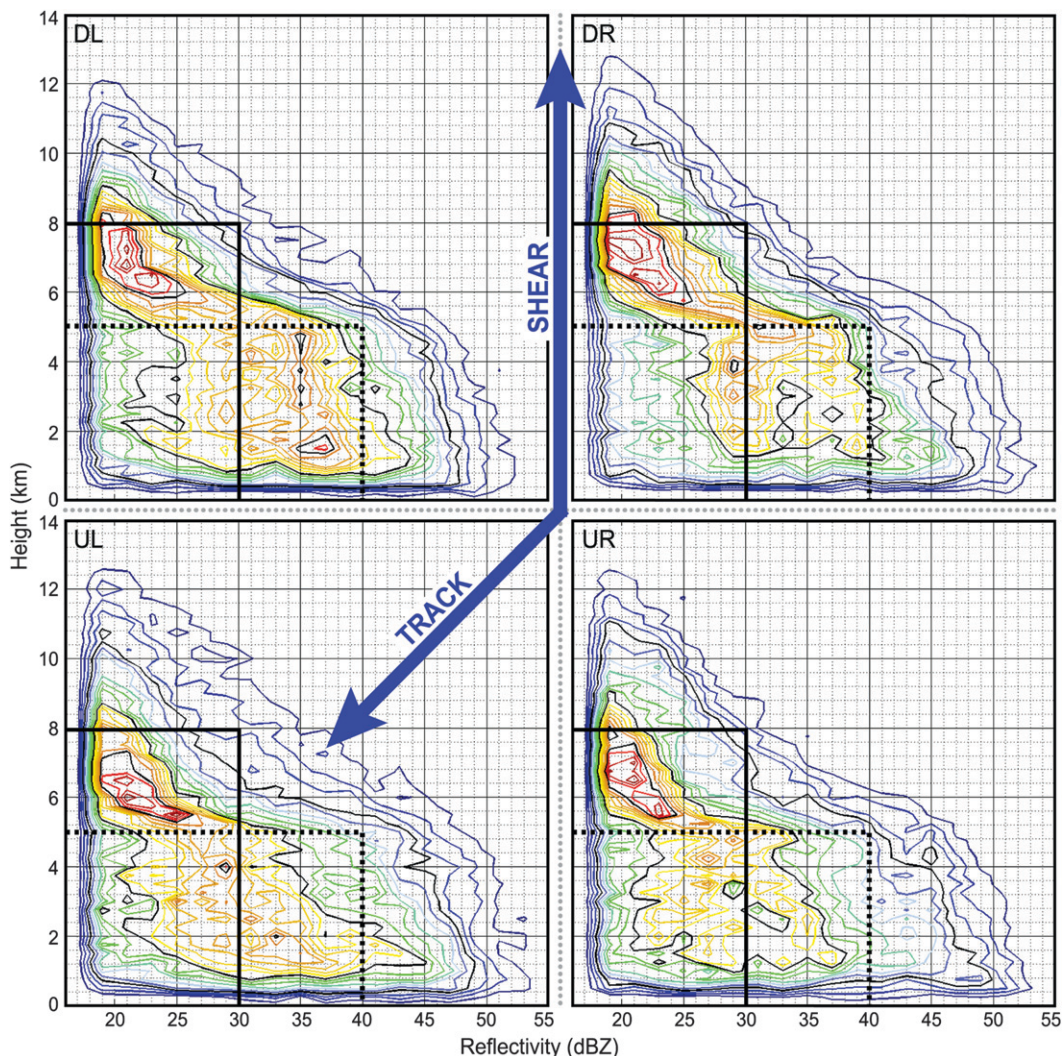


FIG. 5. As in Fig. 4, but contours represent the frequency of occurrence relative to the maximum absolute frequency, contoured every 5%. The 20%, 50%, and 80% contours are black for reference. Other details are as in Fig. 2.

In Fig. 5, the presence of intense outliers in the up-shear quadrants could result from the more evenly distributed intense outliers in low-shear eyewalls (not shown). The spread between the less-than-30% outliers and the 30%–50% outliers and modal distribution in the UR quadrant is over 15 dB. These differences are so large that they suggest these outliers are associated with a subset of the data that does not exhibit the same quadrant-to-quadrant progression as most of the dataset. The next subsection identifies this subset as cases where the wind shear and the translation of the storm tend to be nearly equal and opposite.

b. Vertical wind shear versus storm translation

The quadrant-to-quadrant progression of the normalized vertical distribution in the eyewall (section 4a)

generally holds for the different storm groupings, except for the low-shear, CAT45, and high-SST groupings. The lack of conformity of these three categories to the other groupings in terms of their normalized CFADs leads to a discussion of the impact of track speed on eyewall asymmetry, since these three, plus the high-track-speed category, are the only groupings in which the track speed was nearly equal to or greater than the shear magnitude.

The average shears of all of the cases have strong westerly components, with the overall average being due westerly, whereas the average tracks for all of the cases are primarily toward the northeast. The separation between the two vectors ranged from 100° to 180° (Table 2). Rogers et al. (2003) and Chen et al. (2006) indicate that such a vector difference should nonetheless result in DL asymmetry in the total rain rate field, although the

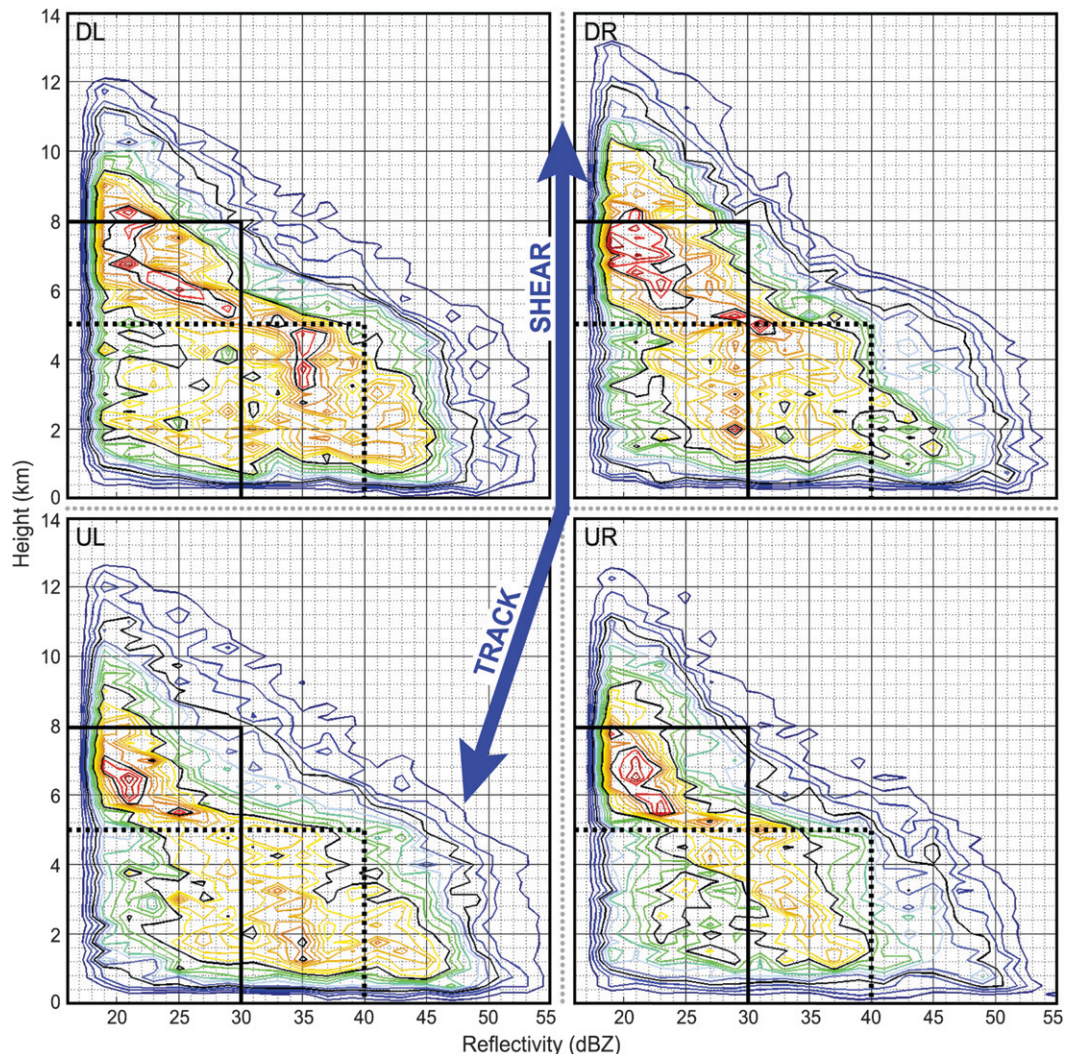


FIG. 6. As in Fig. 5, but only for storms with SST $> 28^{\circ}\text{C}$ (high-SST grouping in Table 1). The pixel count for each quadrant is listed in Table 3.

strength of the asymmetry can be weakened if the shear is weak and if the shear direction is either across or opposite to the track direction. This section seeks to determine whether it is the strength of the shear alone or the strength of the shear relative to the track speed that encourages a change in precipitation mechanisms and/or placement around the eyewall.

The cases that differed from having a full, intense DL quadrant and a weak, sparser UR quadrant were the CAT45, low-shear, and high-SST categories. The low-shear cases were the only grouping that had a nearly 180° separation (177°) between the translation and shear vectors. The low-shear cases have an average shear magnitude of 5.1 m s^{-1} ($850\text{--}200 \text{ hPa}$) $^{-1}$ and an average track speed of 5.7 m s^{-1} , with a maximum number of reflectivity points in the DL quadrant but very little

difference between the other three quadrants ($\sim 3\%$ difference between the DR and UL, $\sim 1\%$ difference between the UL and UR). The high-SST cases have a 162° separation between the translation and shear vectors, an average shear magnitude of 7.2 m s^{-1} ($850\text{--}200 \text{ hPa}$) $^{-1}$, and a track speed of 5.6 m s^{-1} , with a maximum of points in the DL quadrant, very similar DR and UL quadrants ($<1\%$ difference), and a minimum in the UR that is about 8% less than the DR and UL. This distribution of points, as well as the shear and track magnitudes, is very similar for the CAT45 cases, although with a smaller separation of 148° and a UR that is 15% less than the DR and UL.

These three groupings share subtle changes in the progression of the vertical distribution around the storm. Figure 6 shows the CFADs for the high-SST cases. As

mentioned in section 3d, a unique feature of the high-SST profiles is the abundant presence of intense high outliers, especially in the less-than-20% outliers (dark blue contours). These outliers are present symmetrically around the storm, although with a slight lessening in height in the DL quadrant. What is most interesting about this case, and the feature that it shares with the low-shear and CAT45 cases (not shown), is what occurs in the UR quadrant: in both the modal distribution and the 30%–50% (teal and green) outliers, the low-level intensity increases by about 5 dB relative to the UR in Fig. 5. The height of the 21–24-dBZ echo also increases by about 0.5 km in both the modal and 30%–50% outliers in all three cases. This result suggests that there is more new development in this quadrant for these three categories than there are in any of the others.

Cyclonically around the eyewall, the modal distribution gains intensity in the upper levels and a broader distribution in the lower levels of the DR quadrant. In the high-SST cases (Fig. 6), this low-level spread becomes even larger in the DL while the upper levels narrow and lose height; in the other two groupings (not shown), the modal distribution becomes highly uniform and less intense at all levels. For all three groupings, the UL quadrant's upper-level distribution is mostly unchanged, although the peak shifts slightly leftward. In the UL quadrant, the low levels in the low-shear and CAT45 groupings (not shown) lose the distinctive spread into higher values seen in the other cases, whereas the low levels in the high-SST cases (Fig. 6) remain somewhat intense. The UR quadrant CFAD in Fig. 6 resembles the DR quadrant CFAD in Fig. 5, and it resembles the purely convective CFAD of Fig. 2c, with the sloping modal distribution and relative absence of lower reflectivities below approximately 4 km. These results suggest that the UR quadrant tends to have convection forming within it whereas it does not in other groupings, thus shifting some of the vertical distribution progression one quadrant clockwise and thereby suggesting that the convective initiation tends to be one quadrant farther upshear in this case.

The convective generation zone being shifted into the upshear right quadrant may result from the high-SST cases having translation vectors nearly opposite in direction and approximately equal to the shear direction. Such a situation engenders increased surface convergence on the down-track side (Shapiro 1983). This increased convergence would lessen the convection suppression usually present in the UR quadrant. However, this behavior seems to occur regardless of the magnitude of the shear or track speed, as long as they are nearly equal in magnitude or the track speed is greater than the shear magnitude and the directional separation is sufficiently

large. The high-track-speed cases (not shown), have an average shear magnitude of 8.7 m s^{-1} ($850\text{--}200 \text{ hPa}$) $^{-1}$ and an average track speed of 7.2 m s^{-1} , with a separation of 130° . Although the difference between the vectors is as small as the three groupings mentioned above, this grouping has a similar vertical distribution progression to that seen in Fig. 5, and slightly more pixels counted in the UL than the DR. This result suggests that the enhanced convergence may in that case be favoring the left-of-shear side of the storm. In contrast, the low-track-speed cases have a bigger difference between the track (3.7 m s^{-1}) and shear [8.0 m s^{-1} ($850\text{--}200 \text{ hPa}$) $^{-1}$] magnitudes, but the separation is 148° , which is the same as the CAT45 grouping. The vertical distributions of the low-track-speed and CAT45 groupings share many similarities, but the pixel distribution is not as even as it is in the CAT45 grouping, which may be a result of the stronger tangential circulation of the CAT45 grouping more evenly distributing the rainfall (Chen et al. 2006). These hypotheses would be interesting to test in cases where both the track speed and the shear speed are greater than 10 m s^{-1} ($850\text{--}200 \text{ hPa}$) $^{-1}$, but this would be difficult since hurricanes do not tend to last long in such conditions and such situations are usually poleward of the TRMM orbit.

5. Conclusions

Our three-dimensional TRMM PR dataset and an objective definition of the eyewall region has led to an instructive statistical climatology of the vertical distribution of precipitation radar echo within the eyewalls of Atlantic basin tropical cyclones that reach great intensity. The eyewall is found generally to have a deep (high altitude) and intense (high reflectivity) mean structure, which is undoubtedly related to the secondary circulation of the cyclone. The general eyewall structure has deeper and more intense outliers, which are likely associated with buoyant convective towers superimposed upon the mean circulation. Intensity differences and variations in sea surface temperatures are related to whole-scale shifts in the distributions, with stronger storms having more intense and deeper modal and outlier distributions than their weaker counterparts, and with colder SST storms having a lack of deep, intense outliers.

The vertical distribution of radar echo in the eyewall varies with respect to the environmental shear vector on a quadrant-by-quadrant basis. We have been able to distinguish between where precipitation is produced in the eyewall and where it falls out. CFADs of the total pixel counts of TRMM PR echo show that the primary fallout region is in the downshear-left quadrant of the eyewall, in agreement with previous studies. By

normalizing the CFADs by the maximum number of pixel counts, we have shown that convective generation of the precipitation occurs one quadrant upwind, in the downshear-right quadrant. This conclusion expands upon the conclusions of Black et al. (2002), who, from two aircraft data case studies, concluded that convective updrafts tend to be triggered on the upshear side of the storm. Our results more specifically show that the triggering begins in the downshear-right quadrant. The CFADs of the downshear-right quadrant have a younger convective character, with more intense upper-level echo and a relative absence of weak echo at lower levels. In the downshear-left quadrant, we find a more mature mixture of intense convective and stratiform echo characterized by a broader (more heterogeneous) low-level distribution of echo intensity, including a substantial amount of weaker echo at lower levels. Progressively downwind, the normalized CFADs have noticeably less intense echo and indicate an increasing presence of fallout of ice particles producing a brightband signature. The latter indicates that the fallout of ice particles generated upstream is increasingly prevalent azimuthally downwind. Marks and Houze (1987) showed that ice particles convectively generated at upper levels can circulate great distances around the eyewall.

Most groupings of PR data (storm strength, shear, SST, and track speed) followed this general pattern of progression around the eyewall. However, certain subgroupings exhibited instructive exceptions. The CAT45, low-shear, and high-SST categories were the only three in which the shear was less than or nearly equal to the track speed and the track speed was nearly opposite in direction. This configuration exhibited the occurrence of intensely convective echo in the upshear-right quadrant not seen in this quadrant in the other storm groupings, suggesting that the track speed was compensating for the convective suppression typically seen in this region. This behavior seems to occur as a relative difference between the track and shear, and is not necessarily dependent on the shear being weak.

All of these observations suggest that vertical wind shear is the dominant factor in the placement of precipitation around the tropical cyclone, but that other factors in the environment can influence how and where the particles are generated. These results may assist in evaluating model performance in duplicating precipitation structure within tropical cyclones. Future work will include expanding the dataset to all of the tropical cyclone basins, as well as examining the other precipitation regions of the storm.

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