Vertical Structure of Tropical Cyclones with Concentric Eyewalls as Seen by the TRMM Precipitation Radar

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(Manuscript received 29 April 2011, in final form 25 August 2011)

ABSTRACT

Ten years of data from the Tropical Rainfall Measurement Mission satellite’s Precipitation Radar are analyzed to determine the typical vertical structure of the concentric eyewalls of tropical cyclones undergoing eyewall replacement. The vertical structure of the secondary (outer) eyewall is different from the primary (inner) eyewall and also different from the eyewall of single eyewall storms. The upper-troposphere portions of the outer eyewalls are like the rainbands from which they evolve. Their lower-tropospheric portions are more intense and more uniform than rainbands of single eyewall storms, suggesting that these secondary eyewalls are forming from rainbands undergoing axisymmetrization and building from below. The inner concentric eyewalls are more strongly affected by shear than are the eyewalls of single eyewall storms, while the outer eyewalls are relatively unaffected by shear, which suggests the outer eyewall is amplifying the shear-induced asymmetry of the inner eyewall.

1. Introduction

Typically the inner regions of a mature tropical cyclone exhibit one clearly defined eyewall and one or two large principal rainbands, with the occasional presence of smaller intense secondary bands (Willoughby 1988; Houze 2010). A bridge of light stratiform precipitation can provide a connection between the eyewall’s intense ring of convective precipitation and the mixture of heavier stratiform precipitation and pockets of convection in the rainband complex (Marks and Houze 1987), although in more intense storms this region between the eyewall and the rainbands is sometimes precipitation-free (Willoughby et al. 1984). This common configuration of storms exhibiting a single eyewall changes with the development of concentric eyewalls. In concentric eyewall cases, a quasi-circular region of high reflectivity and a corresponding wind maximum form outside of, and concentric to, the primary (inner) eyewall region (Willoughby et al. 1982). A light precipitation or precipitation-free lane, commonly known as the moat, forms between this secondary eyewall and the primary eyewall. If a full eyewall replacement cycle occurs, this secondary eyewall contracts and induces subsidence in the region immediately outside the primary eyewall. The secondary (outer) eyewall eventually takes over when the primary eyewall dissipates (Shapiro and Willoughby 1982; Willoughby et al. 1982; Houze et al. 2007a), although occasionally this eyewall replacement fails (Willoughby 1990).

Since the eyewall replacement cycle seems to occur most frequently in intense storms and has significant impacts on the vorticity, wind, and heating distribution within the storm, understanding this process is critical for improving intensity prediction and understanding tropical cyclone dynamics. Several observational case studies have documented the eyewall replacement process once it is underway (Black et al. 1972; Black and Willoughby 1992; Franklin et al. 1993; Dodge et al. 1999), although only recently has high-resolution direct dual-Doppler analysis of a concentric eyewall case become available (Houze et al. 2007a; Didlake and Houze 2011). Several modeling studies provided significant insights into the possible dynamics governing eyewall replacement (Kossin et al. 2000; Rozoff et al. 2006, 2008; Terwey and Montgomery 2008; Judt and Chen 2010; Qiu et al. 2010). Until recently (Houze et al. 2007a), the short duration of the process (typically about 12 h) and the lack of predictability in real time have made in situ observations of concentric eyewall behavior and confirmation of those

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DOI: 10.1175/JAS-D-11-0119.1

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modeling results difficult. Some attempts have therefore been made in using satellite techniques to study concentric eyewalls (Kuo et al. 2009), but they rely on passive microwave data that lack the three-dimensional structure of the convective features being studied.

This study statistically analyzes 1997–2007 data collected by the Tropical Rainfall Measurement Mission Precipitation Radar [TRMM PR; see Kummerow et al. (1998) for details] in the Atlantic and northwestern (NW) Pacific basins. The objective of the research is to take advantage of the long-term statistics offered by the TRMM PR to compensate for the lack of time continuity in the data on any one storm. The vertical distribution of precipitation revealed by the active high-resolution PR dataset provides insight into the common precipitation features seen within concentric eyewalls and vertical structure information unavailable in other satellite data, thus providing a baseline comparison for observational and modeling studies. After describing our dataset and methods of analysis in section 2, section 3 details the general features of the primary eyewall, moat, and secondary eyewall. Section 4 compares the asymmetric structure of a single eyewall with the asymmetric structure of the primary eyewall and the secondary eyewall in concentric eyewall cases. In section 5 we synthesize the results and present our conclusions.

2. The TRMM PR, CFADs, and radial and quadrant analysis

We use the TRMM PR version-6 2A25 reflectivity data (TSDIS 2007) to obtain a three-dimensional view of reflectivity structure. The approximately 250-m resolution (at nadir) of the PR makes it ideal for evaluating changes in the vertical distribution of precipitation. The approximately 215/247-km swath width (before/after the boost in orbital altitude that occurred in August 2001) and the roughly twice daily sampling (for a given location) have provided numerous overpasses of tropical cyclones. The horizontal resolution is 4.3/5 km (pre-/postboost). 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 advantageously provides a somewhat more complete view of any single storm.

Following Houze et al. (2007b), 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 contoured frequency by altitude diagrams (CFADs; Yuter and Houze 1995). Reflectivity values in the Cartesian grid were counted in 1-dB bins every 0.25 km in height. We only included reflectivity data above the minimal detection of the radar (~17–18 dBZ).

As in Hence and Houze (2011), we use CFADs 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. The mean, standard deviation, skewness, and excess kurtosis (kurtosis − 3; see DeCarlo 1997) are calculated on these raw CFADs. For plotting purposes, the CFADs were normalized by the maximum frequency in the sample (Houze et al. 2007b; Hence and Houze 2011). 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, as well as bringing any peaks in the distribution to the same magnitude for each computed CFAD. This normalization does not change the shape of the distribution, but it allows every profile to be plotted on the same scale. A more complete discussion of this normalization is included in Hence and Houze (2011).

This study uses the storm center, intensity, and eye diameter from the International Best Track Archive for Climate Stewardship (Knapp et al. 2010). Our analysis includes TRMM overpasses of storms within the Atlantic and NW Pacific basins between 1998 and 2007 that reached category 4 (59–69 m s$^{-1}$; Saffir 2003) or 5 (>69 m s$^{-1}$) sometime during their lifetimes. Only overpasses occurring when the storm intensity was at least category 1 (maximum sustained wind > 32 m s$^{-1}$) are included. We estimated 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. All of the overpasses included in this study have the storm center contained within the TRMM Microwave Imager’s (TMI’s) swath width (Kummerow et al. 1998; 760 km preboost, 878 km postboost). The TMI 37- and 85-GHz data and the PR data (when available) were used together to identify concentric eyewall cases and to determine eye diameters when necessary. Since the 37-GHz channel is sensitive to rain, this gives us an estimate of the eye diameter closer to the surface than the 85.5-GHz channel, but they are used in combination because of the 37-GHz channel’s low resolution. In the case of an eyewall with broken echo coverage, estimates of the eye diameter are made on the inner edge of 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 size. 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.

Data from 65 storms (26 Atlantic, 39 NW Pacific) included 37 overpasses of storms exhibiting concentric eyewalls. The criteria used to determine concentric eyewall cases were 1) a ring of high reflectivity existing outside of the eyewall having low-level reflectivity intensities similar to those of the primary eyewall; 2) a still-present primary eyewall, although a complete circle of reflectivity was not required; 3) concentric eyewalls having circular geometry, meaning that the reflectivity feature did not depart from the boundaries of an annular region defined by the objective method below, to distinguish them from spiraling rainbands; and 4) the innermost regions of the storm at least partially covered by the TRMM PR. Because of this last criterion, all of the 37 overpasses contain data from the primary eyewall, moat, and secondary eyewall. All cases not meeting these four criteria were considered single eyewall cases.

Applying these criteria, a total of 371 overpasses of single eyewall cases were identified. However, since the TMI and PR swaths are much different in width, only 164 overpasses of the single eyewall cases contain PR data in the eyewall region. For these cases, the storm-center and eye-diameter reports establish the eye radius $R_e$, which marks the inner boundary for the eyewall region 1. As in Hence and Houze (2011), we divide the storm into a series of annuli of increasing diameter. The outer edge 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. Eight subsequent annuli are defined by their outer boundaries, which are multiples of $R_1$, such that $R_2 = 2R_1$, $R_3 = 3R_1$, ..., $R_9 = 9R_1$. An example of this method is illustrated in the first figure of Hence and Houze (2011). Because of particle advection away from the storm center, the eye estimates may bias slightly large, resulting in a slight bias in the region definitions, but the bias would be small relative to the area each region covers.

Statistics are computed for each of the nine annular regions. The objective technique used by Hence and Houze (2011) to determine the annular regions for single eyewall cases, although attempted, did not suffice to generate statistics for the concentric eyewall cases because the width of the moat and the location of the secondary eyewall were variable. To clarify the statistics, we subjectively adjusted the boundaries of the primary eyewall $R_1$, the moat $R_2$, and the secondary eyewall $R_3$ on the basis of their PR and TMI presentation. The average dimensions of the three regions, and their single eyewall counterparts, are listed in Table 1.

As in Hence and Houze (2011), this study uses a quadrant-by-quadrant analysis to study how features vary around the storm. As in our previous study, 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 (Kalnay et al. 1996). 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 vector-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. The quadrants are defined counterclockwise from the direction of this mean shear vector. The averages of these interpolated shear
vectors for the respective samples are shown in Table 1. This mean shear calculation was also performed for a ring 200–800 km from the storm center, as done in Chen et al. (2006), and our results are strongly consistent with theirs. However, the 500–750-km ring was used to eliminate, as much as possible, the influence of the storm’s wind field.

3. Structure of the primary eyewall, moat, and secondary eyewall

To characterize the unique features of concentric eyewall cases, we compare the reflectivity CFADs of the inner three regions of the concentric eyewall cases with those from the single eyewall cases. The left column of Fig. 1 shows the normalized total accumulation CFADs of the concentric eyewall cases’ primary eyewall (region 1; Fig. 1a), moat (region 2; Fig. 1c), and secondary eyewall (region 3; Fig. 1e) regions. The right column of the figure shows the corresponding region-1, -2, and -3 CFADs of the single eyewall cases (Figs. 1b,d,f, respectively). 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.

The general differences between the concentric and single eyewall cases are highlighted in Figs. 2a and 2b, which show the maximum reflectivity reached by the 30%, 50%, and 70% contours in the plotted CFADs below 4.5 km. In the concentric eyewall cases, the maximum reflectivity is highest in the primary eyewall (red bar, Fig. 2a) at the 30% and 50% contour intervals (pale blue contour and black contour bordering yellow region, respectively, Fig. 1). At the 70% contour interval (orange contour, Fig. 1), the maximum reflectivity of the secondary eyewall (blue bar, Fig. 2a) is equal to that of the primary eyewall. This result is partially predetermined by the methodology, since during case selection the secondary eyewall was required to have low-level reflectivities comparable to the eyewall. The moat maximum reflectivity (green bar, Fig. 2a) is distinctly less than either of these two regions.

In the single eyewall cases (Fig. 2b), the reflectivity intensity in the eyewall (red bar) is the greatest and drops off monotonically with radius for all three contour intervals. For the 30% contour, the step downward in reflectivity intensity is steep to region 2 (green bar, Fig. 2b), but for the other contour intervals the decrease is less severe. This step-down in reflectivity intensity with radius in the single eyewall cases is distinctly different from the U-shaped change of reflectivity intensity with radius seen in the concentric eyewall cases (Fig. 2a). This finding is again partially a result of the methodology, as mentioned above. Nevertheless, we see that the primary concentric eyewall and single eyewall share relatively similar reflectivity intensities (at the 30% and 70% contour intervals), the moat is significantly weaker in reflectivity intensity than region 2 of the single eyewall cases at all intervals, and the secondary eyewall is significantly more intense than region 3 of the single eyewall cases at all intervals. These differences in reflectivity intensity point to a difference in processes occurring in concentric versus single eyewall cases. Note that these results only apply to the precipitating pixels seen by the PR, more specifically only to reflectivities above the PR’s minimal detectable threshold of about 17 dBZ. The number of precipitating pixels counted in this study and the total number possible for all of the accumulated volumes are listed in Table 1.

Figures 2c and 2d show the fractional areal coverage of precipitating pixels as a function of height. For a given region, the areal coverage calculation divides the total number of precipitating pixels accumulated from the overpasses at a particular altitude by the accumulated total number of possible pixels. We believe that the fractional areal coverage is easier to think about than the absolute area, and it also accounts for the pre-/postboost change in pixel size mentioned in section 2.

In the concentric eyewall cases, the primary eyewall displays a gradual decrease in coverage from about 1.75 km to the melting level and then drops off more rapidly with height above (red line, Fig. 2c). This decrease with height is primarily a signature of the slope of the eyewall as well as the subsidence in the eye affecting the inner edge of the eyewall cloud. The moat (green line, Fig. 2c) has an even steeper decrease in coverage with height below the melting level, with subsidence in the moat (Houze et al. 2007a) being the likely reason. Also, the overall coverage is less at all levels in the moat, consistent with the precipitation coverage of the moat tending to be sparse. The secondary eyewall (blue line, Fig. 2c) is unique in that the areal coverage is more constant with height below the melting level than the primary eyewall, and the secondary eyewall has significantly greater total coverage at all levels. This greater overall coverage is partially a result of the case selection, since the secondary eyewall was required to be fully circular. Above the melting level (~5 km), the coverage of the secondary eyewall decreases more rapidly with height than either the primary eyewall or the moat, indicating a limit to the vertical transport of particles in this region. However, these characteristics of the secondary eyewall profile point to a full reflectivity field below that limit, which indicates that a robust transport of particles...
Fig. 1. CFADs of TRMM PR reflectivity data for all of the 1998–2007 overpasses of storms that ultimately reached category-4 or -5 intensity, for the total points of (a) region 1 (primary eyewall) of concentric eyewall cases; (b) region 1 (single eyewall) of single eyewall cases; (c) region 2 (moat) of concentric eyewall cases; (d) region 2 of single eyewall cases; (e) region 3 (secondary eyewall) of concentric eyewall cases; and (f) region 3 of single eyewall cases. 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 (in 250-m increments, or bins) and the abscissa is reflectivity (dBZ; in 1-dB bins). The 8-km and 25-dBZ levels are indicated by the black solid lines, and the 5-km and 35-dBZ levels are indicated by the black dotted lines for ease of reference. The 20%, 50%, and 80% contours are in black for reference.
was occurring vertically, radially, and/or tangentially in the lower portion of the secondary eyewall.

In the single eyewall cases (Fig. 2), the fractional coverage is similar among the three regions. Some slight differences are, however, evident: in the low levels, region 2 (green line, Fig. 2d) has the greatest total coverage, followed by regions 3 (blue line) and 1 (eyewall; red line), respectively. Because of a more gradual decrease in coverage with height, the eyewall (region 1) eventually has equal coverage to region 2 by 9 km. This change above the melting level indicates the robust vertical transport of particles within the eyewall, and the radial transport of those particles outward. The single eyewall has the same vertical characteristics as the primary concentric eyewall (red line, Fig. 2c), with a decrease in coverage with height in the low levels that sharpens in upper levels. The vertical profiles of the other two regions (green and blue lines, Fig. 2d) resemble those of the secondary concentric eyewall region (blue line, Fig. 2c), with a more constant areal coverage below the melting level and a sharper decrease in coverage above. The higher overall areal coverage of region 2 (green line, Fig. 2d), especially in the upper levels, indicates that this region is likely receiving larger and/or a greater number of particles radially from the eyewall, since otherwise the profile is identical in shape to region 3 (blue line).

From the above discussion, we see that in the concentric eyewall cases, the inner (dying) eyewall retains a vertical
structure similar to the primary eyewall of single eyewall storms. The outer (secondary) eyewall is more robust in the sense that it has much greater fractional areal coverage at all altitudes than the inner eyewall. The rapid drop-off of fractional areal coverage above 5 km in the outer eyewall suggests, however, that it also has some aspects of the structure of the noneyewall (rainband) convection that occupies regions 2 and 3 of single eyewall cases. This result is consistent with the idea that the secondary eyewall of the concentric cases forms out of rainband material but restructures itself from the bottom up as the secondary eyewall forms. The following subsections will delve further into the region-1, -2, and -3 features of the concentric eyewall cases.

a. The primary eyewall

The CFAD of the primary eyewall (Fig. 1a) exhibits many characteristics in common with all tropical cyclone eyewalls, as described by Hence and Houze (2011): an intense and deep reflectivity distribution with intermittent (outlier) echoes of even greater depth and intensity. The peak of the low-level distribution occurs just below 35 dBZ, and the modal reflectivity distribution extends from about 25 to 44 dB. The outliers vary from minimal detectable to about 50 dB. In the upper levels, the modal distribution extends to about 9 km for 20 dBZ, but the outliers continue upward to nearly 12 km. Although the decrease in reflectivity with height in the modal distribution is rapid above the layer of melting ice, the outliers decrease more slowly with height, indicating a wide variety in the sizes and/or quantities of particles reaching high altitudes.

These characteristics are further drawn out by Fig. 3, which shows the mean, standard deviation, skewness, and excess kurtosis of the CFADs at every level as functions of height. The primary eyewall distribution (red lines, Figs. 3a,c,e) has a high mean, greater than 40 dBZ at the lowest levels, decreasing to 35 dBZ by the melting level, and decreasing further to 22 dBZ at 11 km (red line, Fig. 3a). The standard deviation is also high, being close to 10 dB at the lowest levels, slowly decreasing to about 7.5 dB by the melting level, and continuing to decrease to about 3 dB by 10 km. The entire primary eyewall distribution is negatively skewed, indicating that the bulk of the distribution is in higher reflectivities that tail toward weaker values, but this skewness moderates toward a more even distribution in the upper levels (red line, Fig. 3c). The excess kurtosis is also negative at all levels, indicating a flat and shouldered distribution (red line, Fig. 3e). Together these moments of the distribution indicate both the strength of the overall circulation of the primary concentric eyewall and the variability in its structure with height. Specifically, they indicate that the primary concentric eyewall distribution is particularly influenced by the presence of intense outliers.

These characteristics are similar to those seen in single eyewalls (Figs. 1b,d,f). The low-level peak of the distribution of the single eyewalls is less intense, likely because the single eyewall cases contain storms of all intensities (category 1–5), whereas the concentric eyewall cases' storm intensities range between a strong category 2 and a weak category 5. The standard deviation within the single eyewall is greater and the decrease in reflectivity with height is less (red line, Fig. 3b), suggesting that suppression of the more intense convection is occurring in the primary eyewall of concentric cases, perhaps as a result of it being in a state of decline.

Thus, the statistics do not show a dramatic change in reflectivity structure in the primary concentric eyewall while an active secondary eyewall is in place, although the circulation is not as deep as that of a single eyewall, and it contains fewer intense outlier cells. These results suggest that while the primary eyewall is still active, it retains its basic vertical structure until it dissipates. Because of the methodology, the concentric eyewall storms are likely in a weakening phase (Sitkowski et al. 2011), so capturing the primary eyewall in varying phases of decline likely introduces some variability into the statistics. To test the robustness of these results, we subsampled the 166 single eyewall overpasses’ region-1 data into 1000 randomly chosen sets of 37 overpasses (same sample size as the set of concentric eyewall samples). The mean and standard deviation profiles of the primary concentric eyewall was weaker and less varied in the upper levels than the envelope containing 999 of the 1000 means and standard deviation profiles of the subsampled single eyewall groups in the manner discussed above (Figs. 4a,b). However, as shown in Henc and Houze (2011), this vertical structure is not symmetric around the entirety of the eyewall. How this structure changes around the primary eyewall and how this differs from the usual progression of reflectivity around the eyewall, will be discussed in section 4.

b. The moat

As mentioned before, the moat is generally categorized by the significantly weaker and/or missing precipitation between the primary and secondary eyewall. What precipitation remains gives interesting insights into the structure of the moat. The moats in this sample varied in width between 4.5 and 57.5 km (not shown), with an average of about 20 km (Table 1). As seen in Fig. 1c, the low-level reflectivities are generally at least 5 dB weaker than in the primary or secondary eyewall, although some slightly more intense and deep echoes appear in the outliers. Interestingly, almost all of the upper-level reflectivities
came from the NW Pacific cases, with the Atlantic cases showing fewer and weaker upper-level reflectivities (not shown).

In contrast with the primary concentric eyewall (or the secondary), the moat distribution is marked by a comparatively low mean and standard deviation (green lines, Fig. 3a), indicating weaker and more uniform precipitation. The low-level skewness is negative, but unlike the primary eyewall the moat skewness is positive above 8 km, indicating that the upper-level reflectivities are

FIG. 3. (a) Mean reflectivity (solid lines) and standard deviation (dashed lines) as a function of height of region-1 (primary eyewall; red line), -2 (moat; green line), and -3 (secondary eyewall; blue lines) concentric eyewall CFADs. (b) As in (a), but for the region-1 (single eyewall, red line), -2 (green line), and -3 (blue lines) single eyewall CFADs. (c) Skewness as a function of height of region-1 (primary eyewall; red line), -2 (moat; green line), and -3 (secondary eyewall; blue lines) concentric eyewall CFADs. (d) As in (c), but for the region-1 (single eyewall; red line), -2 (green line), and -3 (blue lines) single eyewall CFADs. (e) Excess kurtosis as a function of height of region-1 (primary eyewall; red line), -2 (moat; green line), and -3 (secondary eyewall; blue lines) concentric eyewall CFADs. (f) As in (e), but for the region-1 (single eyewall; red line), -2 (green line), and -3 (blue lines) single eyewall CFADs.
bulked into lower intensity bins with a greater tail toward higher reflectivities (green line, Fig. 3c). The excess kurtosis is also negative at low levels and positive at higher levels with a maximum at 8 km, indicating a highly peaked upper-level distribution (green line, Fig. 3e).

These characteristics are a hallmark radar signature of stratiform precipitation, which is generally light to moderate in intensity, and horizontally and vertically uniform except for the rapid increase in reflectivity at the melting level known as the bright band (Yuter and Houze 1995; Houze 1997). These features result in a tightly packed, highly uniform, upper-level profile above a brightband signature in the melting layer, and a broader but still relatively uniform lower-level profile. However, unlike the stratiform precipitation seen in mesoscale convective systems, the stratiform-like precipitation seen in tropical cyclones is as likely occur as a result of ice particles being transported over large distances and slowly falling out than from local growth of particles in mesoscale updraft motion outside of the eyewall. Thus, the precipitation in the moat region seems most likely to be a combination of echoes from the primary eyewall in cases where the primary eyewall was not entirely circular, transport of ice particles outward by the primary eyewall circulation, and local relatively weak convection that has not been completely suppressed.

c. The secondary eyewall

Given that the cases selected were required to have both a primary and secondary eyewall, the vertical structure described here refers to the developing secondary eyewall that has formed but not taken over as the primary eyewall. We see that the secondary eyewall at this stage has a vertical structure unlike that of either the primary concentric eyewall or of the single eyewall in nonconcentric eyewall cases. It seems reasonable to conjecture

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**Fig. 4.** (a) Mean reflectivity as a function of height of the total sample of the single eyewall (region 1, single eyewall cases), primary eyewall (region 1, concentric eyewall cases), and the secondary eyewall (region 3, concentric eyewall cases), with 1000 randomly chosen subsamples of the single eyewall region-1 data (black lines). (b) As in (a), but for standard deviation. (c) Mean reflectivity as a function of height of the total sample of region 2 of the single eyewall cases and the secondary eyewall (region 3, concentric eyewall cases), with 1000 randomly chosen subsamples of the single eyewall region-2 data (black lines). (d) As in (c), but for standard deviation.
that the secondary eyewall's vertical structure becomes that of a single eyewall storm once the primary eyewall has fully dissipated and its radial outflow no longer confines the secondary eyewall to lower levels.

What makes the secondary concentric eyewall unique at the intermediate stage investigated here is its uniformity and intensity, as seen in Fig. 1e. The low-level modal distribution spans only 10 dB, compared to 15–20 dB in the primary concentric eyewall and 20 dB in the single eyewall (cf. Figs. 1a,b). The vertical extents of the echoes are relatively modest compared to the other two eyewalls, with the modal distribution reaching about 9 km and the outliers reaching 10.5 km. The outliers are much more compressed around the modal distribution at all levels, which is distinctly different from either of the other two kinds of eyewalls.

The most distinct difference in the secondary eyewall distribution is that this distribution is tightly centered on relatively high reflectivity values of 35–37 dB. Note the relative absence of lower tropospheric reflectivity values less than about 30 dBZ. This combination of intensity and annular uniformity is not seen anywhere else within a tropical cyclone. This type of distribution does not occur in any primary or single eyewall: a category 4–5 single eyewall has that intensity (or greater) but not the uniformity, and storms located over marginal sea surface temperatures tend toward that uniformity but not that intensity (see Hembre and Houze 2011 for details). As seen in Figs. 1d,f, the regions just outside of the single eyewall (i.e., rainbands) have high upper-level uniformity in their distribution, indicating large quantities of ice. The less uniform lower-level distribution in the rainband regions indicates a wider range of light to moderate rain. A pinching of the rainband CFADs just above the melting layer suggests a distinct particle regime change between the upper and lower layers of the rainband regions, which is distinctly unlike the smoother transition seen in the single-eyewall CFAD (Fig. 1b). The region-2 CFAD of the single eyewall cases (Fig. 1d) in particular has some intense outliers and some echo heights reaching 11.5 km, likely resulting from upper-level transport of particles from the eyewall as well as the intermittent presence of intense convective cells. Except for the highly intense and uniform low-level reflectivities, the secondary concentric eyewall CFAD above the melting level shares these characteristics with the region-2 and region-3 CFADs. Comparing the secondary concentric eyewall CFAD to the rainband CFADs of the single eyewall cases suggests that the secondary eyewall still has some rainband-like characteristics, but that processes occurring at lower levels are intensifying the precipitation, pulling the lower-tropospheric reflectivity distribution over to more intense reflectivities.

The statistics calculated on the secondary eyewall distribution (blue lines, Figs. 3a,c,e) highlight these differences. The low-level mean reflectivity of the secondary eyewall (dBZ; blue line, Fig. 3a) is comparable to that of the primary eyewall, but the upper-level mean reflectivity is like that of the moat, suggesting that the secondary eyewall has an intense circulation that is vertically suppressed. The standard deviation is lower than even that of the moat in low levels but is the same in upper levels (blue line, Fig. 3a). Below 5 km, the secondary eyewall is the most negatively skewed of the three regions, showing the greater tendency of the distribution to be bulked in the higher reflectivity bins; but like the moat and the rainbands of the single eyewall cases, the skewness becomes positive at about 7 km, again showing similarity to the rainbands at upper levels, with the tendency to be evenly distributed at higher levels (cf. the blue lines in Figs. 3c,d).

The excess kurtosis is positive above 7 km (blue line, Fig. 3e). Because of the large amounts of small ice particles circulating around the storm (Black and Hallett 1986, 1999), a peaked upper-level distribution (positive excess kurtosis) and a bright band are ubiquitous features anywhere outside of the eyewall. The excess kurtosis dips negative in the melting layer, representing the above-noted pinching that separates the lower tropospheric CFAD portion from that just above the melting layer, indicating very different distributions in the lower and upper troposphere of the secondary concentric eyewall. These characteristics are again similar to the excess kurtosis profiles of regions 2 and 3 of the single eyewall cases (green and blue lines, Fig. 3f). However, the excess kurtosis of the outer concentric eyewall is especially unique because this distribution is the only one in the entire study that has a positive kurtosis at low levels, indicating a highly peaked, heavily tailed profile (blue line, Fig. 3e). This change in the excess kurtosis is a signature of the tightening in the low-level reflectivity distribution of the secondary eyewall toward higher reflectivities seen in the CFADs. The rainband CFADs, in contrast, are nearly identical in excess kurtosis to the secondary eyewall at the negative peak at 6 km, but only become less negative instead of gaining a positive value at lower levels (Fig. 3f), indicating the more variable distribution in the lower troposphere compared to the developing secondary concentric eyewall.

To summarize, at and above the melting layer, the secondary concentric eyewall shares many of the statistical details of regions 2 and 3 (rainband regions) of the single eyewall cases, suggesting that the secondary concentric eyewall is formed from rainband material. The robustness of these results was born out by subsampling the 166 single eyewall overpasses' region-2 data into 1000 randomly chosen sets of 37 overpasses.
standard deviation profiles of the secondary concentric eyewall are weaker in the upper levels, more intense in the low levels, and less varied at all levels than all of the possible means and standard deviation profiles of the subsampled single eyewall region-2 groups (Figs. 4c,d). Even in low levels, the general shape of the vertical profiles of statistics of the radar echoes in the secondary concentric eyewall is a shifted version of the rainband statistics, while the primary concentric eyewalls and single eyewalls have distinctly different characteristics. The intensity and uniformity of the lower-tropospheric reflectivity distribution shows that the burgeoning secondary circulation forming within the secondary eyewall is generating precipitation at eyewall-like intensities, which is greater than what is typically seen at this radius. This developing circulation, however, is evidently vertically restricted to mostly occurring below the melting layer, as at upper levels little difference is seen between the secondary concentric eyewalls and the rainbands of single eyewall storms. The lower-tropospheric uniformity of the secondary eyewall distribution suggests that axisymmetrization is beginning to help the developing secondary concentric eyewall to coalesce at lower levels. As will be discussed in the next section, the secondary eyewall is highly symmetric at this stage in its development, suggesting an azimuthal uniformity of processes in low levels.

4. Quadrant-by-quadrant variations in the three eyewall types

The statistics discussed above show that the primary and secondary concentric eyewalls have important differences in structure that suggest how the overall processes that may be governing their circulations differ from those in a single-eyewall storm. Like single eyewall cases, concentric eyewalls are often not fully symmetric in reflectivity structure; however, as will be shown below, the primary and secondary concentric eyewalls differ from each other and from single eyewalls.

a. Shear effects on the inner eyewall of concentric eyewall storms in comparison to single eyewall cases

This section examines how the shear-relative asymmetric structure of the primary concentric eyewall compares to the asymmetry seen in single eyewall storms. Hence and Houze (2011) found that although the single eyewall is highly resilient in structure with respect to shear, CFADs show a progression of small differences of reflectivity vertical structure around the single eyewall, most likely related to the progression of shear-induced variation in location of convective cell initiation around the eyewall (Fig. 5 of Hence and Houze 2011). The general characteristics of this progression are apparent in our Figs. 5a and 5b, which include the fractional areal coverage, mean, and standard deviation of the single eyewall quadrant-by-quadrant CFADs (not shown) as seen in this study’s expanded dataset. The low-level means and standard deviations of reflectivity are nearly identical in all quadrants relative to the shear vector (Fig. 5b). The fractional areal coverage indicates how the bulk of the precipitation (as indicated by the lower-tropospheric reflectivity) is deposited in the downshear-left (DL; black lines) quadrant at all levels, and the least in the upshear-right (UR; orange lines) quadrant (Fig. 5a). The upshear-left (UL; teal lines) quadrant has the highest upper-level mean and standard deviation, followed by the upshear-right (UR; orange lines), with lower values found downshear.

As discussed by Hence and Houze (2011), these features, combined with the broadening of the upper-level modal distribution in the downshear-right (DR CFAD; not shown), suggest that the convective cells began their life in the DR quadrant. These cells grow and intensify in the DL quadrant, generating large particles with high reflectivity, but begin to weaken in the UL quadrant before dissipating in the UR quadrant. This process exaggerates with increasing shear, as the NW Pacific single eyewall cases have a somewhat greater left-of-shear asymmetry than the Atlantic single eyewall cases, with the formation region pushing more into the DL quadrant [average shear magnitude = 9.8 vs 8.5 m s$^{-1}$ (850–200 hPa)$^{-1}$, respectively; not shown]. The smaller ice particles that are lofted to upper levels by the intense convection in the DL are quickly transported to appear as more intense upper-level reflectivities in the UL. These weak high-altitude echoes gradually lower in height and weaken in intensity as they travel to UR and DR quadrants. These results are consistent with the inferences of Black et al. (2002), who concluded that the upper-level exhaust of shear-induced convective cells mostly covered the upshear quadrants. Marks and Houze (1987) found that smaller ice particles that reach the eyewall outflow can stay aloft for 1–2 h, and at eyewall tangential velocities they can thus circulate up to 1.5 times around the eyewall. We suggest that while the larger particles are falling out primarily in the DL and UL, the smaller ice particles generated in the DL can fall out in any quadrant, but they register at lower and lower altitudes as they progress downwind.

These general features of the single eyewall exaggerate climatologically in the primary eyewall of a concentric eyewall storm. Figure 5c shows how the precipitation is strongly favoring the left-of-shear side of the primary concentric eyewall, expressed by greater fractional areal coverage in the left-of-shear quadrants. The low-level
means and standard deviations also divide along the shear vector, with the left-of-shear side being more intense (~3–4 dB) and variable than the right-of-shear side (Fig. 5d). This division by shear is more pronounced than in the single eyewall storms (cf. Figs. 5a,b), suggesting perhaps that the weakening inner eyewall of a storm undergoing eyewall replacement is more susceptible to shear-induced asymmetry than a robust single eyewall not being affected by eyewall replacement. This susceptibility occurs even though the average shear magnitude of concentric eyewall cases is lower than in the single eyewall cases (Table 1). The individual basins again

![Areal coverage](image1)

![Mean and standard deviation](image2)
b. Shear effects on the outer eyewall of concentric eyewalls [average shear magnitude = 8.40 vs 8.49 m s$^{-1}$ (850–200 hPa)$^{-1}$, respectively; not shown]. The NW Pacific primary eyewalls are also more asymmetric in fractional areal coverage, although similar in intensity, to their single eyewall counterparts, with the average shear magnitude being lower [6.99 vs 9.77 m s$^{-1}$ (850–200 hPa)$^{-1}$, respectively; not shown].

The CFADs for quadrants of the primary concentric eyewall cases (not shown) are similar in quadrant progression to what was described for the single eyewall, although the right-of-shear quadrants’ outliers are more strongly suppressed, suggesting that the convection formation region may have shifted more into the DL. This asymmetry shifts above the melting level with the more intense reflectivities being in the upshear quadrants (Fig. 5d), again suggesting that the upshear quadrants are receiving the lofted ice particles from the intense convection in the left-of-shear quadrants. The enhanced convection asymmetry within the primary concentric eyewall may explain why the upper-level upshear asymmetry is more pronounced than what is seen in single eyewall cases. These general results are consistent with those seen by Franklin et al. (1993) in Hurricane Gloria (1985), who found that, as in single eyewall storms, environmental vertical wind shear influenced the distribution of convection around the eyewall.

b. Shear effects on the outer eyewall of concentric eyewall storms and comparison to the inner eyewall

The lower-tropospheric echo intensity in the secondary concentric eyewall is greater in the left-of-shear quadrants (Fig. 5f). However, unlike the primary concentric eyewall, this difference is only about 1 dB and only extends to the melting level—above that, the mean reflectivity is nearly identical in all quadrants. The standard deviation is also highly similar at all levels. The main asymmetry appears in the fractional areal coverage, which is generally larger to the left of shear (Fig. 5e). These differences between the left and right of shear indicate the nature of the wavenumber-1 asymmetry in the reflectivity distribution of the secondary eyewall: the left-of-shear quadrants are slightly more intense than the right-of-shear quadrants and have somewhat more echo coverage. However, there is no indication of a quadrant-to-quadrant progression in the nature of the convection, since the convection in all quadrants appears to be of a similar character. Rather, the convective cells apparently develop in the convectively favored left-of-shear quadrants and are able to develop into slightly stronger and more intense cells, but these cells seem to mostly grow and die close to their originating quadrant. Convection on the convectively disfavored side of the secondary eyewall develops but does not reach quite the same intensity. Since the outer eyewall has a much greater diameter and lower tangential wind speeds than the primary concentric eyewall, it is more difficult for particles to be advected circumferentially to a different quadrant of the storm. The right-of-shear quadrants are too far away to receive particles generated in the left-of-shear quadrants, so it is likely that their reflectivity distribution is locally generated.

It is interesting that the secondary concentric eyewall exhibits such a comparatively small asymmetry in convective intensity even though, as noted in the previous subsection, the primary concentric eyewall exhibits an exaggerated version of what is seen in the shear-induced asymmetry of a single eyewall. One possibility is that the primary eyewall is not directly exposed to the large-scale environmental wind shear, and the moat subsidence enhances the shear-induced subsidence effect on the primary concentric eyewall in the upshear quadrants. This explanation would be consistent with the primary concentric eyewall convection being vertically suppressed compared to single eyewall convection (cf. Figs. 5b,d). The primary concentric eyewall would then have less ability to combat the shear-induced asymmetry. Another possibility is that the moat subsidence is asymmetric, as evidenced by the moat tending to contain more precipitation in the left-of-shear quadrants than the right (not shown). However, weakened subsidence in the DL moat where the convection in both the primary and secondary eyewall is most intense seems dynamically inconsistent. More likely, this imperfect moat clearing results from the enhanced particle transport or imperfect boundaries mentioned above. Yet another possibility is that the secondary concentric eyewall’s influence on the radial inflow is somehow asymmetric. This explanation seems somewhat unlikely because the enhanced side of the secondary concentric eyewall does not correspond to the depressed side of the primary eyewall, and the overall features of the secondary eyewall are much more symmetric than the primary eyewall. In other words, convection in the secondary eyewall must be rather axisymmetric in order to have a complete eyewall; otherwise, no hydrometeors would exist to create surface precipitation all the way around the storm. Modeling and Doppler analysis will be required to test these ideas.

c. Schematic of the typical echo pattern of concentric eyewalls relative to the environmental shear

Figures 6 and 7 illustrate schematically the typical structure of concentric eyewalls that can be gleaned from Fig. 5 and other figures in this paper. Figure 6 illustrates
the differences in horizontal reflectivity distribution between the primary and secondary concentric eyewalls. A mostly precipitation-free moat is shown between the two eyewalls, and the sizes of the features are directly proportional to the average eye diameter and primary eyewall, moat, and secondary eyewall widths listed in Table 1. The inner edges of the two eyewalls are concentric, but the outer edges vary in width, related to the fraction of areal coverage shown in Fig. 5. The quadrant with the maximum areal coverage is shown to have the maximum area for that quadrant; the other quadrants are sized downward respectively. The bulk of the precipitation in the primary eyewall, both in amount and intensity, is weighted to the downshear-left side, with the upshear-right quadrant exhibiting a minimum in both, consistent with Fig. 5c. As hypothesized in section 4a, the convective cells are shown beginning their development in the downshear-right quadrant, growing and intensifying in the downshear-left quadrant, and becoming weaker in the upshear-left quadrant, before dissipating entirely in the upshear-right quadrant. The bulking of the precipitation in the downshear-left quadrant of the primary eyewall results in a narrowing of the moat in that quadrant, whereas the moat in the upshear-right quadrant is wider and clearer. As inferred from Figs. 5e,f, the secondary eyewall also exhibits a wavenumber-1 asymmetry in convective intensity. The upshear-left quadrant has the fullest reflectivity field, but the precipitation is most intense in the downshear-left quadrant. As hypothesized in section 4b from Figs. 5e,f, we speculate that convective cells overall generate and disperse more locally than those in the primary eyewall.

Figure 6 also illustrates some idealized particle trajectories inferred from Figs. 5c–f. These trajectories are estimated as in Marks and Houze (1987) and using the azimuthal average low-level winds from Didlake and Houze (2011). With the Marks and Houze (1987) calculation that the larger eyewall particles take about 10 min to fall, this would generously assume that the particles would fall within 36 km in the primary eyewall (traveling at 60 m s\(^{-1}\), or category-4 intensity) or 30 km in the outer eyewall (traveling at 50 m s\(^{-1}\)). As shown in Fig. 6, a large particle could travel from its generation...
almost a full quadrant in the primary eyewall, but because of the large distances in the secondary eyewall a similar particle would only cover a quarter of the downshear-left quadrant. A smaller eyewall particle took 1–2 h to fall out in Marks and Houze (1987). At the same wind speeds, this smaller particle could travel up to 324 km in the primary eyewall and 270 km in the secondary eyewall. As shown in Fig. 6, this translates to a more than complete circuit in the primary eyewall, but less than half a circuit in the secondary eyewall. These differences in transit distances likely explain the differences in horizontal precipitation distribution between the primary and secondary eyewalls.

Figure 7 idealizes a cross section through the strongest and weakest portions of the concentric eyewalls along line AB in Fig. 6. Consistent with Figs. 5c,d, the left-of-shear side A exhibits more intense convection, with high reflectivities reaching higher heights in the primary eyewall. We speculate that the enhanced convection on this side of the primary eyewall would intensify transport of precipitation particles outwards, which would narrow and shorten the moat. As inferred from Figs. 5e,f, convection in this portion of the secondary eyewall is nearly as intense but not quite as tall as the primary. The lack of higher upper-level reflectivities could be a combination of enhanced vertical suppression from the primary eyewall as well as enhanced transport of the smaller precipitation particles downwind. On the right-of-shear side B, the precipitation at all but the uppermost levels and at all radii is lighter (consistent with Figs. 5d,f). The primary eyewall, likely receiving its precipitation from upwind, is shown to be narrower and significantly less intense. As inferred from Fig. 5d, this downwind particle transport is shown to appear especially in the upper levels of the primary eyewall, which have a greater tendency toward higher reflectivities. With a weakened convection in this part of the primary eyewall, the moat is shown to be wider and taller. Consistent with Fig. 5f, the secondary eyewall’s convection on this side is weaker but still present and active, and it is much more similar to its left-of-shear counterpart than the asymmetry seen in the primary eyewall.

5. Conclusions

Statistical analysis of TRMM PR three-dimensional data collected over 10 yr reveals that the secondary (outer) eyewalls of concentric eyewall tropical cyclones exhibit departures in structure from the eyewalls of single eyewall storms and are also different from the primary (inner) eyewall precipitation structure of concentric eyewall storms. The inner eyewalls maintain a deep (high altitude) and intense (high reflectivity) mean structure, similar to the structure described for single eyewalls by Hence and Houze (2011), while they remain active, although they are somewhat less deep than the eyewalls of single eyewall storms. The inner concentric eyewalls are more susceptible to shear asymmetry than are the eyewalls of single eyewall storms. What precipitation exists in the moat is light in intensity and vertically limited. The secondary (outer) concentric eyewall is nearly as intense as the inner eyewall in low levels but it is less deep than the inner eyewall. The secondary eyewall’s precipitation is more intense through the lower troposphere than is precipitation seen at the same radius in single eyewall storms.

The secondary concentric eyewalls examined in this study have formed but not yet replaced the inner eyewalls. At this intermediate stage of development, the secondary eyewalls resemble rainbands in their upper levels and eyewalls in their lower levels. The secondary eyewall has the same highly uniform upper-level distribution and melting signature as the rainbands, indicating a separate ice particle distribution aloft than what is being generated in low levels. However, unlike rainbands, the low-level distribution of the secondary eyewall is both highly uniform and intense. This combination of upper- and lower-level features is completely unique to the secondary concentric eyewalls. The high intensity and great uniformity in the low levels, but rainband-like distribution of reflectivity in the upper levels, suggests that the secondary eyewall is largely made of rainband material that is undergoing modification to form a circular eyewall feature, and that the convective processes creating this new eyewall are building it from below. These convective processes also seem to be highly resistant to environmental vertical wind shear, with the left-of-shear side being only marginally favored for more intense convection with increasing shear.

Future work will expand this type of analysis to the rainband region of the storm (i.e., the region lying radially outside the eyewall regions of both single and concentric eyewall storms). This work could also be explored using the global TRMM dataset and possibly including lightning data from the TRMM Lightning Sensor (LIS) or other lightning networks. The ideas germinated in these statistical studies will need to be examined in the context of high-resolution models resolving the convective-scale substructure of precipitating clouds of tropical cyclones.

Acknowledgments. Tia Lerud and Tyler Burns assisted with case identification, database creation, and analysis. We are grateful to Anthony Didlake and Stacy Brodzik for help and comments. Beth Tully provided graphics and editing support. NCEP Reanalysis data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado (http://www.esrl.noaa.gov/psd/). This research was
sponsored by NSF RAINEX Grants ATM-0432623 and ATM-0743180, NASA PMM Grants NAG5-13654, NNX07AD59G, and NNX10AH70G, NASA Earth and Space Science Fellowship NNX06AF17H, and a NASA Space Grant Fellowship.

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