Secondary Wind Maxima in Hurricanes: Airflow and Relationship to Rainbands

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ABSTRACT

Aircraft flight-level data from 787 radial legs in 20 hurricanes are analyzed to identify the composite kinematic structure in the hurricane eyewall, and especially with secondary horizontal wind maxima (SHWM) that occur outside the eyewall. Similar to previous studies, analysis of the flight-level wind data in the eyewall reveals radial convergence near the radius of maximum wind (RMW), and the highest frequency of updrafts and the largest upward mass transport radially inward of the RMW.

More than 20% of the flight legs contain substantial secondary horizontal wind maxima of specified strength and length. The kinematic structure associated with SHWM is similar to that of the hurricane eyewall with radial convergence near the radius of maximum wind and a preferred location for maximum upward motions and upward mass transport just inside the RMW. Statistical analysis confirms the similarity in characteristics between radial and vertical velocities of the eyewall and near the SHWM. In addition, for both the eyewalls and SHWM, the radial velocity composite results show that the radial mass transport in the planetary boundary layer must be largely confined to the lowest 1000 m.

Lower fuselage radar reflectivity data from 13 of the hurricanes are used to assess whether the outer wind maxima are associated with rainbands, and vice versa. In the radial legs with SHWM for which radar data were available, the secondary horizontal wind maximum was frequently associated with a mesoscale reflectivity feature (rainband). In contrast, many rainbands, more than 70%, were without wind maxima. The results from this study show that to some extent an outer eyewall or rainband with SHWM can act as a barrier to inflow to the inner eyewall. Additionally, it is possible that thermodynamic modification of inflow air may occur as a result of convective-scale vertical motions associated with a rainband. In those cases when an outer rainband encircles the eyewall, it is possible that these factors act together with subsidence to weaken the inner eyewall.

1. Introduction

Rainbands are prominent features on radar plan views of hurricanes. They have been observed since the 1940s but are poorly understood even today. In the early years, lack of quantitative description was a major obstacle. By the mid-1970s, research aircraft had been equipped with quantitative digitally recording weather radar, as well as inertial navigation systems giving accurate winds. One group of case studies (Barnes et al. 1983; Powell 1990a,b) shows examples of airflow relative to particular rainbands, emphasizing that convective updrafts and downdrafts are coherently organized on the mesoscale (band scale). These studies demonstrated that rainbands with strong convective cells could replace the inflowing boundary layer air with downdraft air that had lower temperature and specific humidity, leading to speculation of whether such rainbands might sap the vigor of eyewall convection and storm intensity (Barnes et al. 1983). Rainbands without strong convection have been found to lack such downdrafts (Barnes and Stossmeister 1986).

These case studies were incomplete in the sense that the aircraft could stay with a rainband for just a few hours, and could not simultaneously investigate the rainband and also the airflow within and above the boundary layer between the rainband and the eyewall. They were also limited to asymmetric storms of minimal-to-moderate strength. That limitation is not coincidental. Symmetric storms tend to be stronger, and in situ probing of the boundary layer, at altitudes as low as 150 m in the above studies, is hazardous.

Nevertheless, exciting new results were obtained from studies of symmetric storms. Willoughby et al. (1982) described how outer rainbands often propagate inward to form a concentric ring around the eyewall that eventually chokes and replaces the original, inner eyewall. The double eyewall, formerly viewed as a curiosity (Jordan and Schatzle 1961), is now recognized...
**Table 1. Inventory of tropical cyclones, the distribution of the flight level data by altitude, and the number of secondary horizontal wind maxima (SHWM) for each storm. Table constructed following the format of Willoughby (1990).**

<table>
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<tr>
<th>Radial legs</th>
<th></th>
<th>900 mb</th>
<th>850 mb</th>
<th>700 mb</th>
<th>600 mb</th>
<th>Total</th>
<th>SHWM</th>
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<td></td>
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<td>0</td>
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<td>24</td>
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**Table 2.**

<table>
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<th>Total</th>
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<th>497</th>
<th>153</th>
<th>70</th>
<th>787</th>
<th>173</th>
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</table>

Another purpose is to clarify the relationship between rainbands and secondary wind maxima. We suspect that it is not appropriate to use the terms interchangeably, so we also ask the following questions: Given a secondary wind maximum, what is the probability that it coincides with a rainband? Conversely, given a rainband, what is the probability that it coincides with a secondary wind maximum?

**2. Data**

This study uses flight-level data from the archive of National Oceanic and Atmospheric Administration (NOAA) aircraft observations for 13 years (1977–89) of Atlantic basin tropical cyclones. The data are maintained by the NOAA Hurricane Research Division (HRD) and include storm-relative observations from 72 flights into 20 hurricanes yielding 787 radial legs (Table 1). Over 93% of the radial legs are from NOAA WP-3D (P-3) research flights with the remaining legs from NOAA C-130 flights. In addition to the flight-level measurements, horizontal maps of reflectivity from the lower fuselage (LF) radar onboard the P-3 are used. The radar database includes composites and single sweep images of radar reflectivity from 30 flights into 13 hurricanes (Table 2). These images represent 220 radial legs, about 25% of the radial legs available from the flight-level data.

**a. Flight-level data**

Aircraft instrumentation records flight-level kinematic and thermodynamic measurements at 1 Hz during each flight. The 1-Hz data were converted into storm-relative coordinates so that this dataset contains storm-relative radial, tangential, and vertical wind components, temperature, dewpoint temperature, and the aircraft location in latitude and longitude. In the earlier flights of the dataset, flight-level winds were determined by dual inertial navigation equipment (INEs) updated with periodic (~10 s) Omega corrections combined through a Kalman filter thus reducing errors due to a Schuler oscillation. In later flights, the INEs were decoupled from the Omega positioning and allowed to record freely. Corrections to the flight-level data using Omega information were made in postflight renavigation. Corrected INE navigation was used to determine a storm track so that subtraction of the aircraft track to derive the storm-relative winds removed the accumulated position and horizontal velocity errors due to drift that may account for errors of about 30 cm s⁻¹ over the duration of a flight. In our judgment, a greater source of error in the storm-relative winds results from uncertainty in the location of the storm center. The algorithm of Willoughby and Chelmon (1982) minimizes these errors as well. A detailed review of the aircraft instrumentation is found in Jorgensen (1984a).

In this study, only radial legs flown at atmospheric pressures of at least 600 mb in hurricanes (sustained
winds greater than 64 kt or 33 m s\(^{-1}\)) are considered. A radial leg is defined as an inbound penetration to the hurricane center or an outbound exit from the storm center. Specific flight levels investigated include 600, 700, 850, and 900 mb. As seen in Table 1, the majority of the radial legs, 63%, are at 850 mb. Table 1 shows that the sampling of flight levels is not evenly distributed among the different storms. Some flight levels are dominated by only a few storms, for example, the majority of flight legs at 600 and 900 mb are from only two hurricanes. However, the distribution problem is minimized as data from different levels are combined in the calculations.

This database employs an overlapping ‘‘pup-tent’’ averaging method that partitions the storm-relative 1-s data into 0.5-km radial bins using a center-weighted averaging technique. The averages are computed with a weighting function that decreases linearly from 1.0 at the bin center to zero, 1 km from the bin center (Willoughby et al. 1982). Each radial leg extends out to a maximum of 150 km from the hurricane center and thus consists of up to 300 data points at 0.5-km resolution. The data processing procedures are further described in Willoughby et al. (1982) and Willoughby (1990).

b. Aircraft radar data

The LF radar data are expressed as time composites or single sweeps of horizontal reflectivity patterns. The LF radar operates at a wavelength of 5.59 cm and possesses horizontal and vertical beamwidths of 1.1° and 4.1°, respectively. Additional characteristics of the radar system are noted in Jorgensen (1984a).

Single sweeps of the LF radar reveal reflectivity features close to the aircraft, especially those on the convective scale. In contrast, time composites of radar reflectivity resolve mesoscale precipitation patterns and are useful in identifying rainbands at large ranges from the aircraft. The radar composites of this study were created following the procedure of Marks (1985). This procedure uses the reflectivity observed in several individual radar sweeps and creates a single, storm-relative horizontal map of maximum reflectivity detected in each bin during the compositing time interval. This compositing technique minimizes the effects of inadequate beam filling, attenuation, and aircraft roll inherent in single radar sweeps.

The radar composites include data for the duration of the inbound and outbound radial legs. To minimize the smoothing of reflectivity gradients of features moving relative to the storm center, the compositing period does not exceed 1 h. The typical composite interval is about 45 min. The 110 radar images represent 220 radial legs (Table 2). This is the maximum number of radar images the authors could retrieve from the HRD archives. Due to radar malfunction, tape errors, or calibration problems, radar composites could not be created for the remaining legs.

<table>
<thead>
<tr>
<th>Hurricane</th>
<th>Year</th>
<th>Number of flights</th>
<th>Number of radar images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anita</td>
<td>1977</td>
<td>1</td>
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</tr>
<tr>
<td>Frederic</td>
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<td>Diana</td>
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<td>5</td>
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<tr>
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<td>Florence</td>
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<td>Hugo</td>
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</tr>
<tr>
<td>Jerry</td>
<td>1989</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>30</td>
<td>110</td>
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</table>

During the time represented by a composite, reflectivity features move downwind. As a result, the compositing technique occasionally maps a single convective feature as a mesoscale entity. Single sweep images from the LF radar, chosen near the midpoint of each radial leg, are created to identify individual convective cells with reflectivity that may have been elongated downwind in the compositing.

3. Methodology

a. Definition of a secondary horizontal wind maximum

Each of the 787 radial legs of the dataset were examined to identify the occurrence of a mesoscale horizontal wind maximum outside the primary wind maximum associated with the hurricane eyewall. To eliminate subjectivity in the definition of secondary horizontal wind maxima (SHWM), specific criteria were adopted. Following the definition of Samsury and Rappaport (1991), SHWM were defined as secondary peaks in the storm-relative horizontal wind field which, over a distance of at least 10 km along the flight track, remained more than 5 m s\(^{-1}\) higher than the wind speed at the local minimum between the respective inner and outer peaks (Fig. 1). These criteria were chosen to delineate between peaks in the wind profile due to turbulent motions and small-scale convective phenomena and mesoscale secondary wind maxima probably associated with hurricane rainbands. Of the 787 radial legs studied, 173 legs from 17 hurricanes were found to have SHWM that met these criteria (Table 1).

Table 1 notes the number of radial legs per storm and the number of legs with SHWM. More than 40% of the radial legs in some of the hurricanes (Allen, Gloria, Gilbert, Dean, Gabrielle) had SHWM, whereas other storms (Danny, Emily, Joan) were completely
without. There was large variability in the shape of the wind profiles and the location and magnitude of the secondary wind peaks. Figure 2 highlights three typical differences in the horizontal wind structure of profiles with SHWM. Hurricane Gilbert has extremely peaked primary and secondary wind maxima. Most of the radial legs with this type of wind profile are found in Hurricanes Allen and Gilbert. The profiles of Hurricanes Alicia and Gloria represent more frequently occurring horizontal wind profiles. Alicia’s overall wind distribution is broader than Gilbert, and the SHWM is less pronounced and located further away from the hurricane center. A very flat wind profile is seen in Hurricane Gloria. The SHWM is greater than 120 km from

Gloria’s center and is less peaked than either of the other two examples.

Table 3 shows the distribution of radial legs as a function of quadrant for the complete dataset and for the radial legs with SHWM. In each quadrant, the number of radial legs in the entire dataset varies by only a small amount. As shown in Table 3, the northwest quadrant contains the smallest percentage of radial legs (22%) and the southwest quadrant has the largest percentage (27%). In contrast, the majority of the radial legs identified with SHWM, approximately 30%, are in the southeast quadrant. Although the southwest quadrant was most heavily sampled, only 19% of the radial legs with SHWM are there, the least of any quadrant. The environmental flow through the storm, as discussed by Willoughby et al. (1984), may be responsible for the lower number of SHWM in the southwest quadrant.

b. Kinematic analysis

For each of the 787 radial legs, a primary radius of maximum tangential wind ($R_v$) was identified. The
mean maximum tangential wind for the entire dataset is 44.3 m s\(^{-1}\) with the mean \(R_1\) at 37.2 km. The cumulative frequency distribution of the radius of maximum wind (RMW) is seen in Fig. 3. The curve is remarkably similar to the distribution of RMWs from an independent dataset of about 500 radial legs from Shea and Gray (1973). In both datasets, the median RMW is close to 30 km.

Tangential wind profiles are often approximated by the modified Rankine vortex, \(\text{const} = V_\infty r^x\), (Hughes 1952), where \(V_\infty\) is tangential wind and \(r\) is radius. The exponent \(x\) was determined for the 787 radial legs of the dataset (outside the RMW) yielding a mean value of 0.42 and a standard deviation of 0.21. Although the mean exponent agrees with the values noted by Riehl (1963) and Gray and Shea (1973), it is important to stress, as Gray and Shea (1973) did, that there is considerable spread about the mean and individual profiles vary greatly. Further, two issues must be recognized here. First, the distance over which the exponents were calculated differed from leg to leg depending on the amount of data available outside the RMW. Second, the modified Rankine vortex poorly estimates the wind profile of radial legs with SHWM, which were of particular interest in this manuscript. Perhaps future work will investigate whether a wind profile with dual wind peaks might be approximated by two exponents, one for each maximum.

In the 173 radial legs with SHWM, the secondary radius of maximum wind (\(R_2\)) was noted. The mean maximum tangential wind for the secondary wind maxima is 40.5 m s\(^{-1}\) at a mean distance of 90 km from the storm center. Figure 4 shows the average tangential velocity field with respect to \(R_1\) of the entire dataset and \(R_1\) and \(R_2\) for the dual peaked legs. The velocity distributions associated with the primary wind maxima indicate a decrease of 20–25 m s\(^{-1}\) by 10 km inside the RMW with a more gradual drop outside the RMW. These results fit the accepted hurricane model with horizontal winds decreasing as the calm eye is approached and also lessening outside the eyewall wind maximum. Tangential winds of the SHWM have a smaller overall maximum yet the peak remains approximately 6 m s\(^{-1}\) greater than the mean tangential wind 10 km inside \(R_2\).

Considering that the SHWM exist away from the hurricane eye, it is not surprising that the drop-off inside the RMW is less pronounced compared with that of the eyewall wind maxima.

In addition to the tangential wind fields, radial and vertical wind fields, and associated vertical mass transport were also calculated and composited into radial bins in a coordinate system extending \(\pm 10\) km from the RMW, that is, \(R_1\) for 787 legs and \(R_1\) and \(R_2\) for 173 legs.

1) RADIAL VELOCITY

The storm-relative flight-level radial velocity data are divided into mid- and lower-tropospheric classes.

![Fig. 4. Composite tangential velocity field within 10 km of the RMW for the entire dataset of 787 radial legs (bold, solid), the first tangential wind maximum of a dual wind profile (173 legs) (dotted), and the secondary tangential wind maximum of a dual profile (173 legs) (dashed).](image_url)

Flight legs at 600 and 700 mb are included in the former; 850 and 900 mb flight legs compose the latter. The composite radial velocity field is determined in 0.5-km increments within 10 km of \(R_1\) and \(R_2\) for each of the legs. Each value of the mid and low-level radial wind fields was calculated as a linear average of all the radial velocities occurring in each 0.5-km bin relative to the tangential wind maximum.

2) VERTICAL VELOCITY AND VERTICAL MASS TRANSPORT

Following the procedures of Zipser and LeMone (1980) and LeMone and Zipser (1980), the flight-level vertical velocity data were analyzed to identify convective-scale vertical motions that satisfied the definition of a convective core, defined as a vertical velocity event for which \(|w|\) is continuously greater than 1 m s\(^{-1}\) for at least 0.5-km horizontal distance. Since the 1-Hz vertical velocity data used in this dataset were partitioned into 0.5-km bins, the horizontal resolution was reduced by about a factor of 4 and the core criteria could be fulfilled by a point from this dataset representing 0.5 km of data.

Prior to identifying the cores in the 787 radial legs of this study, the mean vertical velocity per leg was computed and removed from the data. Zipser and LeMone (1980) noted that large offsets could lead to the identification of spurious updraft or downdraft cores. In addition, Jorgensen et al. (1985) noted that vertical velocity data from C-130 flights into Hurricane Allen were in error leading to leg means exceeding 2 m s\(^{-1}\). To determine which legs these and other flights had vertical velocity measurement problems, a
critical threshold of 1.5 m s\(^{-1}\) for the mean vertical velocity was chosen, and radial legs with vertical velocity leg means greater than the threshold were excluded from the vertical motion statistics. Due to this requirement, vertical velocity data from approximately 4.0% of the 787 legs were omitted from all vertical velocity and transport calculations (Fig. 5a). Of the legs with dual wind maxima, 5 of the 173 leg means were greater than 1.5 m s\(^{-1}\) (Fig. 5b) and were deleted from the data sample.

The number and location of the cores relative to the composite \(R_1\) and \(R_2\) were determined. As in previous work (Zipser and LeMone 1980; Jorgensen et al. 1985; Jorgensen and LeMone 1989; Lucas et al. 1994), several properties of the cores were also calculated. These properties were intercepted length [for convenience we choose to call it approximate diameter (DIAM)], average vertical velocity \((\bar{w})\), and mass transport (MT). The mass transport per core was computed using the equation

\[
MT = (\bar{\rho})(DIAM)(\bar{w}),
\]

where \(\bar{\rho}\) is the average density per leg calculated from the equation of state. No assumption is made about the shape of the core; statistics are representative of a cross-track dimension of 1 m.

The core statistics were partitioned into 2-km bins as a function of distance from the composite RMW, \((\pm0\text{-}2 \text{ km}, \pm2\text{-}4 \text{ km}, \text{etc.})\) for radial legs that possessed only an eyewall wind maximum and those that also contained a secondary horizontal wind maximum. For each of the bins, the number of up and downdraft cores, average DIAM, \(\bar{w}\), and mass transport per core were calculated relative to the composite RMW. The estimated total mass transport, defined as the product of the average mass transport per core with the core frequency in each 2-km bin, was also computed. To eliminate any possible overlap of one core into more than a single 2-km bin, the location of a core relative to the RMW for all calculated core properties was determined to be the distance from the core midpoint to the RMW. All compositing of the flight-level data was relative to the position of the RMW and not to the distance of the feature from the storm center. For example, if the RMW was at 50-km radius from the storm center, the coordinate system extended from 40- to 60-km radius along the radial leg with an origin at 50 km. Figure 2 shows three wind profiles with the 20 km of study outlined for each.

It is possible that the core characteristics determined in this study may be biased too low. Jorgensen et al. (1985) discussed the implications of aircraft penetrations missing the center of a circular-symmetric core. They found that failing to sample the middle of a core with a vertical velocity maximum at the center could result in the average vertical velocity and diameter being biased too small by a factor of 2 and about 22%, respectively. Resulting mass transport calculations could additionally be underestimated by a factor of 2.2. The comparisons of core location and mass flux between primary and secondary wind maxima should be unaffected since these biases apply equally to both maxima.

c. Definition and analysis of a rainband

The extent to which the locations of SHWM and rainbands coincided was examined by comparing flight level data with radar data. We investigated both the frequency of rainbands when a SHWM was identified and the frequency of secondary wind maxima given the existence of a rainband. As with the definition of a sec-
ondary wind maximum, we wanted to limit subjectivity in the determination of a rainband. A method was developed to identify objectively mesoscale reflectivity features that may be associated with rainbands from the composites, and to delineate those rainbands from convective-scale regions of precipitation.

Although the radar composites depict the reflectivity patterns over a large region, the flight-level data characterize only the environment close to the aircraft. We believed precipitation features existing just upwind or just downwind of the aircraft could kinematically impact the wind field measured. Thus, the average reflectivity value within a rectangular area centered on the aircraft position was chosen to be representative of the reflectivity field encountered. This rectangle extended 40 km normal to the aircraft track and 15 km along the flight track (Fig. 6).

Objective criteria were chosen to identify rainbands near the research aircraft. Time series of mean reflectivity as a function of distance from the hurricane center were produced and analyzed to determine the existence of rainbands. To be termed a rainband, two requirements had to be met. The first requirement was that the mean reflectivity value within the rectangular area was greater than 25 dBZ, consistent with the criterion of Barnes et al. (1983). The second criterion was that a secondary maximum of mean reflectivity existed outside the eyewall reflectivity maximum and was at least 6 dBZ higher than the local minimum between the eyewall and the rainband. The maximum in the mean reflectivity distribution of the secondary reflectivity peak marked the location of each rainband. It is important to note that the rainbands identified by this scheme may include both stratiform and convective bands since these criteria do not necessarily discriminate between the two rainband types.

The combination of the size of the rectangular box and the reflectivity criteria effectively eliminated the

![Horizontal map of radar reflectivity from the P-3 LF radar for Hurricane Hugo on 17 September 1989. The east–west line indicates the flight track of the P-3 over the time interval. The rectangular box and accompanying "x" designate the area of the averaging box and location of the aircraft, respectively, at a sample time along the flight track. The domain is 360 km × 360 km.](image)

**Fig. 6.** Horizontal map of radar reflectivity from the P-3 LF radar for Hurricane Hugo on 17 September 1989. The east–west line indicates the flight track of the P-3 over the time interval. The rectangular box and accompanying "x" designate the area of the averaging box and location of the aircraft, respectively, at a sample time along the flight track. The domain is 360 km × 360 km.
majority of the isolated cells, yet included organized, mesoscale regions of precipitation that might be associated with substantial localized horizontal wind maxima. As mentioned in section 2b, single sweep images were used in addition to the radar composites to identify any convective-scale features that appeared to have been aliased into the mesoscale due to ‘‘smearing’’ by the compositing procedure. This smearing occurred in 12 cases, and those precipitation features have been excluded from all rainfall statistics.

4. Results

a. Radial velocity and vertical velocity fields with respect to the primary horizontal wind maxima

Figures 7a and 7b show the composite radial velocity (storm relative) field associated with \( R_1 \) of the full dataset (787 legs) and \( R_1 \) of the radial passes with a SHWM (173 legs), respectively. In the low troposphere for both eyewall regions, there is inflow toward the storm center outside \( R_1 \) and flow away from the storm center inside \( R_1 \). Thus, with respect to \( R_1 \), inflow converges from both sides. At midlevels, the overall composite field reveals strong outflow from the storm center in the 4 km inside \( R_1 \), with weaker outflow outside \( R_1 \) (Fig. 7a). Once again, there is a convergence of radial wind near \( R_1 \). Figure 7b also shows mid-tropospheric convergence near \( R_1 \) for the legs with dual horizontal wind maxima.

Although in both these eyewall cases, the radial velocity field reveals convergence near \( R_1 \), the magnitudes of the radial velocity for the lower tropospheric flow are much smaller than expected within the lower levels of a hurricane. It is strongly suggested that the frictional boundary layer is not well sampled. Inflow angles of only 3° are estimated from the mean tangential and radial flows. Riehl (1963) and Powell (1987) identified inflow angles of at least 15° within the planetary boundary layer (PBL) of hurricanes, and the results of Jorgensen (1984b) imply inflow angles of up to 25°. Although 900-mb flight legs are included in each composite field and might be within the PBL, fewer than 15% of the legs contributing to the lower tropospheric component in Figs. 7a and 7b are at 900 mb. Furthermore, these legs, when composited separately (not shown) do not have appreciably larger radial inflow components. The clear implication of these results is that the storm-relative radial inflow to the eyewall is largely confined to the lowest 1000 m.

Figure 8a shows the frequency of cores as a function of distance from the eyewall tangential wind maximum for 757 radial legs of the dataset; vertical velocity data from 30 legs with leg means exceeding the 1.5 m s\(^{-1}\) threshold were not included. Updraft cores occurred most often within the 4 km inside \( R_1 \). Their frequency decreased inside \( R_1 \) to a minimum 10 km away. Outside \( R_1 \), updraft cores were found fairly frequently and uniformly with a slight minimum occurring in the 2 km outside \( R_1 \). Overall, there were slightly more updraft cores in the 10 km inside \( R_1 \) compared to outside (Table 4). There does not appear to be a preferred location for downdraft cores, although the greatest frequency of cores existed 6–10 km outside \( R_1 \) (Fig. 8a). Downdraft cores outside \( R_1 \) (within 10 km) outnumbered those inside 303 to 183 (Table 4).

Similar to Fig. 8a, the greatest number of cores within 10 km of \( R_1 \) of the radial legs with SHWM were in the 4 km inward of \( R_1 \) (Fig. 9a). The number of updraft cores inside \( R_1 \) was greater than updraft cores outside by nearly 2:1 (Table 4). The distribution of
Fig. 8. Composite (a) core frequency, (b) mass transport, and (c) estimated total mass transport fields relative to \( R_1 \) for eyewalls of the full dataset. Positive columns denote updraft cores; negative columns represent downdraft cores. The bold vertical line at zero km is the location of \( R_1 \). Negative values along the abscissa are bins toward the hurricane eye; positive values are those away from the hurricane eye.

Fig. 9. As in Fig. 8 except for eyewalls of radial legs with dual horizontal wind maxima.

downdraft cores varied considerably in radius, but most downdraft cores were outside \( R_1 \).

In spite of the relatively large number of updraft cores outside \( R_1 \) in Fig. 8a, the updraft cores from 0 to 4 km inside \( R_1 \) were associated with the greatest average mass transport (Fig. 8b). The mass transport produced by these updraft cores was nearly twice as large as the largest of the other bins with the exception of 0–2 km outside of \( R_1 \). The downward mass transport associated with downdraft cores was typically smaller than the updraft mass transport and maximum values were 2 km outside \( R_1 \). In general, a similar distribution of mass transport is seen in Fig. 9b for the radial legs with dual wind maxima. The largest mass transport of Fig. 9b occurs with the updraft cores in the 6 km inside \( R_1 \) and the 2 km outside \( R_1 \). As in Fig. 8b, the average mass transport of the downdraft cores is fairly uniform throughout the 20 km.

Figures 8c and 9c are the product of Figs. 8a and 8b and Figs. 9a and 9b, respectively, and show the weighted distribution of mass transport given the number of cores represented in each 2-km bin. As expected, inside \( R_1 \) upward mass transport is much greater than downward mass transport. In contrast, outside \( R_1 \)

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**Table 4. Number of up and downdraft cores for the primary (\( R_1 \)) and secondary wind maximum (\( R_2 \)) inside and outside the RMW.**

Statistics exclude cores from radial legs with vertical velocity leg means exceeding 1.5 m s\(^{-1}\).

<table>
<thead>
<tr>
<th></th>
<th>Updraft cores inside the RMW</th>
<th>Updraft cores outside the RMW</th>
<th>Downdraft cores inside the RMW</th>
<th>Downdraft cores outside the RMW</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 ) for all legs (757)</td>
<td>271</td>
<td>268</td>
<td>183</td>
<td>303</td>
</tr>
<tr>
<td>( R_1 ) for dual cases (168)</td>
<td>133</td>
<td>73</td>
<td>98</td>
<td>111</td>
</tr>
<tr>
<td>( R_2 ) for dual cases (168)</td>
<td>140</td>
<td>53</td>
<td>53</td>
<td>81</td>
</tr>
</tbody>
</table>
downward mass transport is slightly greater than upward mass transport. The distribution of total mass transport is dominated by a maximum in upward mass transport within 6 km of $R_1$. The total upward mass transport associated with cores from the full dataset 4 km inside $R_1$ represents 34% of the total mass transport across the 20 km of study (Fig. 8c). Similarly, more than 38% of the total mass transport seen in Fig. 9c is upward in the 6 km inside $R_1$.

These results, showing radial convergence near the RMW and a preferred location for updraft cores and upward mass transport inside the RMW, are consistent with the eyewall results of previous studies such as Shea and Gray (1973), Jorgensen (1984a,b), and Jorgensen et al. (1985).

b. Radial velocity and vertical velocity fields with respect to SHWM

Figure 10 presents the composite, storm-relative, radial velocity field associated with the 173 SHWM. The resulting radial velocity field is similar to radial flow fields identified with eyewall regions associated with $R_1$ (Figs. 7a, 7b) and in Jorgensen (1984a). There is radial convergence at both low- and midtropospheric levels near $R_2$. Relative to $R_2$, there is inflow on both sides at low levels; at midlevels, there is slight inflow from the outside of $R_2$ and stronger inflow from the inside of $R_2$. In addition, the magnitudes of the composite radial velocity are very close to those seen in Fig. 7 for the hurricane eyewall. Relative to $R_2$, composite inflow values for the secondary wind cases actually exceed those for the eyewall cases. Once again, these values represent the hurricane environment above the PBL. As for the eyewalls, the clear implication is that the storm-relative radial inflow to $R_2$ is largely confined to the lowest 1000 m. This finding is consistent with the case studies of rainbands of Barnes et al. (1983) and Powell (1990a,b), which show that the radial inflow velocity decreases sharply between 150 and 1000 m. Barnes and Powell (1995) also stress the shallowness of the inflow in their case study.

The plot of core frequency (Fig. 11a) relative to the composite $R_2$ shows most of the updraft cores are inside $R_2$ with the maximum number closest to $R_2$. In fact, there are 2.6 times as many updraft cores inside $R_2$ as outside it. In contrast to the updrafts, downdraft cores are distributed uniformly about $R_2$, similar to those near $R_1$ (Figs. 8a, 9a) and in the eyewall studies of Jorgensen et al. (1985) and Shea and Gray (1973). Additionally, updraft cores outnumber downdraft cores by 2.6:1 inside $R_2$. This result is similar to the findings of Barnes et al. (1983) and Powell (1990a). In their case studies of rainbands in Hurricanes Floyd (Barnes) and Josephine and Earl (Powell), they found more than 60% of the drafts inside the rainband axis to be updrafts.

The average mass transport per core is plotted as a function of radial distance from the composite $R_2$ in Fig. 11b. Most of the average upward mass transport is inside $R_2$ where it is much larger than the downward mass transport. Outside $R_2$, the upward and downward

![Diagram](image-url)
average mass transports are nearly equal. The total mass transport field (Fig. 11c) is almost exclusively upward inside $R_2$ and weakly downward outside it. The total upward mass transport inside $R_2$ represents 68% of the total mass transport across the entire 20-km domain. This is in agreement with Jorgensen et al. (1985), who found that about 64% of the total mass transport near the eyewall was just inward of the radius of maximum wind.

c. Location of SHWM and rainbands

Although there were 173 radial legs with secondary wind maxima, radar data could be retrieved only for 45 of those radial legs. Of those 45 legs, 27 (60%) had rainbands within 10 km of a SHWM. An additional 7 SHWM were within 20 km of a rainband so that 76% of the radial legs that had a SHWM also contained a rainband within 20 km. Figure 12 shows a radar composite of Hurricane Gilbert (Fig. 12a) and the positions of $R_2$ and rainbands within 10 and 20 km on the south and north, respectively (Figs. 12b,c). The secondary peaks of mean reflectivity are larger than those of the eyewall because the area that was included in the eyewall average encompassed low values of reflectivity from inside and outside of the eyewall region. The eyewall mean reflectivities were not adjusted because the main concern in this study was the reflectivity associated with hurricane rainbands.

One reason that only about 75% of the wind maxima occurred within 20 km of the reflectivity maxima was that the criteria chosen to identify rainbands could not be met. It was often seen from the radar images that high reflectivities associated with the wind maxima were embedded within a large region of precipitation similar to the connecting band identified by Willoughby et al. (1984). Because the surrounding dBZ values were relatively uniform, the reflectivity gradients were not large and the reflectivity perturbations did not fit the stated criteria, which required a secondary reflectivity peak to be at least 6 dBZ higher than surrounding values. Seven SHWM were within 20 km of identifiable reflectivity features that exhibited this type of precipitation structure. One such event from Hurricane Gabrielle is shown in Fig. 13. Although the mean reflectivity values about 50 km northeast of the center were greater than 45 dBZ (Fig. 13c), there is not a large enough dropoff in the area-averaged reflectivity outside the eyewall to distinguish the secondary reflectivity feature as a rainband. Visual examination of the reflectivity associated with the remaining four radial legs lacking rainbands within 20 km of a SHWM revealed that all the passes were located within broad areas of precipitation that failed to produce marked fluctuations in the area-averaged reflectivity distributions.

It has been shown that most SHWM are associated with rainbands. Is the converse true? There were 118 precipitation events that met the criteria for rainband identification. Of these, only 34 rainbands (29%) were within 20 km of the location of a secondary wind maxima that met the criteria outlined in section 3a (e.g., Fig. 1; Fig. 12b). As in the analysis of SHWM with rainbands, some of the apparent lack of correlation between rainbands and SHWM is due to the choice of definitions. In some instances, there were small perturbations in the horizontal wind field that did not meet the criteria for a SHWM that may have been associated with rainbands. It is also possible that some of the identified rainbands were the result of rainshfts falling from the bright band outside the eyewall as in Marks and Houze (1987). This stratiform precipitation would not, in general, be expected to be associated with large perturbations in the wind field. In addition, some rainbands not associated with SHWM may produce kinematic perturbations at a height other than that of the aircraft. Nevertheless, it is surprising that so few rainbands, less than 30%, produce a secondary wind maximum. Figure 13c shows an example in Hurricane Gabrielle where a rainband was identified 85.5 km southeast of the eye without a corresponding secondary wind maximum (Fig. 13b).

5. Statistical significance

Given many of the similarities that exist between the kinematic fields associated with the primary (eyewall) and secondary (rainband) horizontal wind maxima, it is important to examine whether the subset of radial legs with dual wind peaks (173 legs) is a representative sample of the total population of 787 flight legs. The frequency distribution of the average tangential velocity per radial leg is seen in Fig. 14. The two plots do appear very different. The Student's t-test confirms that the difference between the two means of the distributions is statistically significant at the 5% level. It is somewhat expected, however, that the overall tangential wind characteristics would differ, given the strong secondary peak that exists along a radial leg in addition to the expected primary wind maximum for "dual" cases. The overall mean of the tangential velocity for legs with dual peaks is in fact more than 4 m s$^{-1}$ higher than that of the entire dataset.

Perhaps of more uncertainty is whether the radial and vertical velocity characteristics of the dataset and subset are statistically different. Analysis of the frequency distribution of radial velocity leg means for the full dataset and the subset of legs with SHWM (not shown) reveal that the two distributions are nearly identical, and the differences between the means are not significant at the 5% level. Moreover, the leg means of vertical velocity for the total dataset and SHWM (Fig. 5) are not significantly different at the 5% level. These results suggest that, with respect to the radial and vertical velocity wind components, the subset of SHWM legs is representative of the total.
Fig. 12. (a) Composite horizontal radar reflectivity of Hurricane Gilbert for 0959–1025 UTC 14 September 1988; (b) tangential wind profile for the same time interval along the flight track; (c) area-averaged reflectivity along the P-3 flight track. The domain in (a) is 360 km × 360 km. The distance of the secondary wind maxima (b) and secondary reflectivity maxima (c) are noted in kilometers. The vertical line at 0 km in (b) and (c) indicates the center of the hurricane.
Fig. 13. As in Fig. 12 except for (a) composite horizontal radar reflectivity of Hurricane Gabrielle for 1941–2011 UTC 3 September 1989.
Although the above statistical tests of the leg means allow the SHWM to be considered a representative sample, it is also important to determine whether the 20 km of wind data that were used to calculate the composite radial velocity field and vertical velocity core characteristics of the full dataset and the SHWM could have come from the same population. The t-test comparisons between the data from the composite radial velocity fields associated with $R_1$ and $R_2$ show that their respective means are not statistically different at a 5% level. Analysis of the vertical velocity data, offsets removed, within the 20-km domain also reveal that the distributions of points associated with $R_1$ and $R_2$ are not statistically different.

Evaluation of t-test results is sensitive to the number of degrees of freedom (DF), and it is possible that a serial correlation exists between different flight legs of the same flight. Thus, in our study, it may be improper to use DF based solely on the number of radial legs in each dataset. The statistical results above were analyzed using both DF (legs) and DF (flights), and the overall results at the 5% level were consistent in each t test.

Although the tangential velocity leg means are statistically different between the full dataset and the legs with SHWM, it is noteworthy that the radial and vertical velocity leg means are so similar. In addition, the similarities between the radial and vertical velocity data of the eyewall and SHWM are striking and provide further evidence that the kinematic structure of SHWM and eyewalls are very much alike.

6. Summary

The results from this study confirm many of the findings of Jorgensen et al. (1985), Jorgensen (1984a,b), and others with a comprehensive dataset characterizing the composite wind and reflectivity for 20 hurricanes. The database included 787 radial legs of storm-relative flight-level data in tropical cyclones of varying intensity. Our composite radial velocity field for the entire dataset shows a convergence of radial velocity at low- and mid-tropospheric levels near the RMW. In addition, maxima in updraft core frequency and upward mass transport exist inward of the tangential wind maximum associated with the eyewall. In contrast, downdraft cores are evenly distributed across the eyewall region and occur less often than updraft cores inside the RMW.

Most importantly, however, this study was one of the first to analyze the kinematic structure associated with substantial secondary peaks of the horizontal wind. We identified 173 mesoscale SHWM from the 787 radial legs available in this study and investigated their composite kinematic structure. Within 10 km of $R_2$, the mesoscale fields of radial velocity, the convective-scale vertical velocity, and mass transport were similar to those in the hurricane eyewall. As with the hurricane eyewall (section 4a; Jorgensen 1984a,b; Shea and Gray 1973), there was radial convergence near the RMW, the preferred location of updrafts was just inside the RMW, and upward mass transport maxima were within 8 km inward of $R_2$. In addition, statistical analysis shows that the radial and vertical velocity data near SHWM are essentially the same as those associated with the hurricane eyewall. These results also support with a large dataset some of the case study findings of Barnes et al. (1983), Barnes and Powell (1995), and Powell (1990a,b) related to rainband kinematic structure. For both the eyewalls and $R_2$, these composite results show that the radial mass transport in the PBL is largely confined to the lowest 1000 m.

In addition to the kinematic structure, we studied the relationship between secondary wind maxima and hurricane rainbands. In the radial legs with SHWM for which radar data was available, a mesoscale reflectivity...
feature frequently could be identified within 20 km of the wind maximum. In contrast, there were many more rainbands without wind maxima. Over 70% of the rainbands that were found could not be linked to any substantial maximum in the horizontal wind field. An important aspect of the relationship between SHWM and rainbands may be the convective or stratiform nature of the rainband, which was not determined in this study. Results indicate that significant secondary wind maxima possess an inflow layer from both sides of $R_i$. It is hypothesized that this radial flow pattern would be more likely to occur in convective rainbands rather than in stratiform bands.

7. Discussion

The eyewall-like structure associated with secondary wind maxima has implications for hurricane intensity change. It seems that the kinematic structure associated with SHWM and accompanying rainbands can provide at least a partial barrier to inflow to the center of the storm on a small scale. Depending on the azimuthal extent of these features, it is possible that a scenario for the weakening of a hurricane might be created. For instance, if our composite radial and vertical wind fields existed throughout a concentric eyewall, it is conceivable that flow to the hurricane center could be disrupted causing a weakening of the inner eyewall as discussed by Willoughby et al. (1982) and Willoughby (1990). Using mass flux measurements of a convective cell in a hurricane, Barnes et al. (1991) also argued that rainbands may partially obstruct inflow to the eyewall.

Shapiro and Willoughby (1982) point to subsidence over the inner eyewall from the upper-level outflow of a developing secondary ring of convection as a means by which an outer eyewall causes a weakening and possible demise of an inner eyewall. They suggest that this eyewall replacement process often results in the weakening of the strength of the hurricane as seen, for example, in Hurricane Gilbert (1988) (Black and Willoughby 1992). While upper-level subsidence likely plays a role in the collapse of the inner eyewall and the subsequent weakening of the hurricane as a whole, there is uncertainty as to how much weakening is due solely to subsidence effects.

The results from this study show that to some extent an outer eyewall or rainband can act as a barrier to inflow to the inner eyewall. Additionally, it is possible that there is some thermodynamic modification of inflow air as a result of convective-scale vertical motions associated with a rainband (Barnes et al. 1983; Powell 1990a,b). It may well be that these factors act together with subsidence to weaken the original eyewall. More research is needed on these issues, and more fundamentally, on the role of rainbands in the hurricane environment. As we reach a better understanding of the mechanisms of eyewall replacement and the adverse or beneficial effects of hurricane rainbands on the overall circulation of a cyclone, we will undoubtedly improve our ability to forecast hurricane intensity changes.

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