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ABSTRACT

This paper describes the boundary layer wind structure and dynamics of Hurricanes Danielle (1998) and Isabel (2003), based on the analysis of high-resolution global positioning system dropwindsonde data and simulation of the flow by a three-dimensional boundary layer model produced by Kepert and Wang. The observations show that the hurricane boundary layer has a complex three-dimensional structure with large variability over small distances. The analysis emphasizes three aspects: the degree of gradient-wind balance, the radially varying depth of the boundary layer, and the strength of the near-surface wind speed relative to that at a higher level. Each aspect is compared both with results obtained in a simulation of the individual storm by Kepert and Wang’s model and with theoretical predictions. The observations show that the boundary layer depth decreases toward the center of the storm, consistent with theoretical arguments. The strongest azimuthal winds occur near the top of, but still within, the frictional inflow layer. These strong azimuthal winds are marginally supergradient in Hurricane Danielle but strongly so in Hurricane Isabel, where the imbalance amounts to approximately 10 m s⁻¹ near the radius of maximum winds and is statistically significantly nonzero. This layer of supergradient flow is surmounted by a layer of outflow, in which the flow returns to gradient balance. The maximum storm-relative azimuthal wind occurs near the left front of Hurricane Danielle, and the strongest inflow is located in the right front. These asymmetries rotate anticyclonically with height, but there is also a clear wavenumber-2 asymmetry superimposed, which shows less rotation with height and is possibly forced by environmental factors associated with the storm’s impending recurvature. In Hurricane Isabel, the azimuthal wind maximum is located in the left rear and the inflow maximum in the left front, with neither showing much tendency to vary in azimuth with height. The ratio of the near-surface wind speed to that farther aloft increases toward the storm center for both storms. The largest values are located near the radius of maximum wind, and in general higher values are found on the left of the storm’s track than on the right. Simulations of the two storms with the boundary layer model are able to explain several of these factors; they also show some ability to reproduce individual dropsonde wind observed profiles. Important is that the model predicts weakly supergradient flow in Danielle and strongly supergradient flow in Isabel, in excellent agreement with the observational analysis. Based on these simulations, physical arguments, and earlier studies, the authors conclude that the differences between these storms in this respect result from their differing radial profiles of gradient wind and argue that the occurrence of supergradient flow in the upper boundary layer of individual hurricanes should be readily predictable.

1. Introduction

Tropical cyclones are among the most destructive of natural phenomena. Understanding the hazard resulting from wind, storm surges, and waves clearly requires a thorough knowledge of the tropical cyclone boundary layer. Recent theoretical and observational work has begun to show that the boundary layer in a tropical cyclone is distinctly different from the atmospheric boundary layer in other situations. The most distinctive observed feature is the marked jetlike maximum at about 500-m height seen in mean and individual wind speed profiles near the eyewall (Franklin et al. 2003;...
Powell et al. 2003); the relationship between the surface winds and those aloft has also received considerable attention (Powell 1980; Powell and Black 1990; Franklin et al. 2003; Kepert 2006a,b). This paper reports analyses of the boundary layer flow in the core of two contrasting hurricanes, Danielle (1998) and Isabel (2003), and further advances our understanding of the unique characteristics of this part of the atmosphere.

Kepert (2001, hereinafter Kep01) and Kepert and Wang (2001, hereinafter KW01) have studied the three-dimensional dynamics of this tropical cyclone boundary layer jet. They show that the supergradient winds in the jet are caused by strong inward advection of angular momentum within the boundary layer and that the necessary inflow is maintained at the jet height against the outward acceleration resulting from gradient imbalance by the upward transport of inward momentum from below the jet. This upward transport occurs by both vertical diffusion and the eyewall updraft. Neglect of the vertical advection terms in the linear model of Kep01 is the main reason that this model and the similar but axisymmetric models of Rosenthal (1962) and Eliassen and Lystad (1977) produce weaker jets than the fully nonlinear model of KW01. Above the jet, the influence of the inward forcing recedes and a weak outflow develops, leading (through angular momentum advection) to a return to gradient balance. The vertical wind shear resulting from the cyclone warm core also contributes to the weakening of the winds above the jet. Kepert and Wang also show that the jet tends to be most strongly supergradient near the radius of maximum winds because of the requirement for strong angular momentum advection and a marked updraft; however, the details depend on the structure of the individual storm. In particular, a storm with a “peaked” wind profile (and consequently a weak absolute angular momentum gradient outside the radius of maximum winds) tends to have a more weakly supergradient jet confined to near the eyewall, and a storm with a flatter profile will have a more extensive area of less strongly supergradient flow. In all cases, the modeled boundary layer depth decreases markedly toward the storm center because of the increasing inertial stability there.

These authors also considered the boundary layer flow asymmetry induced by the storm motion. In the linear solution, the storm-relative asymmetric flow is the sum of two frictionally stalled inertia waves. These are generated by the asymmetric friction due to storm motion, and their vertical structure (phase rotation and decay with height) is such that vertical diffusion alters their phase velocity to be zero; that is, they are locked into position relative to the storm. In the inner core, the weaker of these waves rotates cyclonically and decays rapidly with height; meanwhile, the overall asymmetry is dominated by the stronger, anticyclonically rotating wave, which decays relatively slowly with height. The asymmetric flow in the nonlinear model is similar to that in the linear model. Because of this asymmetric structure, the jet is more strongly supergradient on the left (right) side of a moving storm in the Northern (Southern) Hemisphere.

The surface wind factor is defined as the ratio of the surface wind speed to the speed at some level above the boundary layer and has been widely used operationally as a convenient means of estimating surface winds from observations higher in the storm. Although it is a convenient and widely used parameter, some care is needed with the terminology because high reduction factors are associated with relatively strong surface winds rather than weak ones (as the name might imply). Kep01 and KW01 predicted that the surface wind factor would have a systematic spatial variation within the storm, increasing from 0.6–0.7 in the outer part of the cyclone to 0.8–1.0 beneath the eyewall, and would be greater on the left (right) side of the storm in the Northern (Southern) Hemisphere. Franklin et al. (2003) analyzed a large number of dropsonde wind observations in several hurricanes and found good agreement with these predictions, although the observed left-right asymmetry was a little less than expected.

A number of observational studies have examined the boundary layer of tropical cyclones. Powell (1982), for instance, examined the boundary layer wind field in Hurricane Frederic (1979) while it moved north-northwest from the open Gulf of Mexico to landfall at the Alabama–Mississippi coast. The overwater analysis of Frederic showed that the maximum wind speed was located in the front right region of the eyewall, in agreement with many other studies, and a secondary wind maximum was found at a distance of about 100 km, or approximately 3 times the radius of maximum wind (RMW), north-northwest from the storm center. The surface inflow angle (i.e., the angle between the surface earth-relative wind and a tangent to a circle centered at the storm center) was largest to the right rear of the storm and at a minimum to the left, where there was a region of outflow. Frank (1984) also analyzed the three-dimensional structure of the inflow layer of this storm and found a distinct decrease in the depth of the inflow layer with decreasing radius.

The surface wind field showed an asymmetric structure in Hurricane Alicia (1983) at landfall resulting from the storm translation, the background environmental flow, and the differences in the land–sea roughness (Powell 1987). A strong radial flow asymmetry was found, with surface inflow on the left side of the storm...
and outflow on the right. Because of the storm translation, stronger winds were found on the right side than the left.

For a long time, only sparse data were available from over the ocean, and the surface parameters had to be estimated from the aircraft data. Air-deployed drifting buoys resulted in a considerable improvement, but major progress in improving the accuracy and spatial resolution for atmospheric measurements over data-sparse oceanic areas of the globe was not made until the development of the Global Positioning System (GPS) dropwindsondes and their use for wind-finding in tropical cyclones (Hock and Franklin 1999). Using these instruments, the mean wind speed profile in a hurricane’s inner core from the surface up to 700 hPa was documented for the first time (Franklin et al. 2003). Franklin et al.’s (2003) analysis of this data displayed a broad wind maximum centered at 500-m altitude, which they claim marks the top of the boundary layer. The frictional boundary layer was located below this wind maximum, and the wind decreased nearly linearly with the logarithm of the altitude near the surface. The surface wind beneath the eyewall was on average about 90% of the 700-hPa value. The maximum wind occurred at a higher level (~1 km) in the regions outside the eyewall, and the decrease in wind speed above the top of the boundary layer was much smaller there. Franklin et al. argued that the eyewall profile structure was affected by the wind speed and the vertical motion, where strong low-level downdrafts and enhanced vertical motion are generally associated with higher surface winds. However, we note that calculations of boundary layer flow that resolve height (e.g., Rosenthal 1962; Eliassen and Lystad 1977; Kep01; KW01) produce similar spatial variations of structure within the storm without including these effects. Similarly, depth-averaged boundary layer studies such as Shapiro (1983) and Smith (2003) show that the boundary layer wind is proportionally stronger near the RMW than at large radii.

Analysis of dropsonde wind data in intense Hurricanes Georges (1998) and Mitch (1998) (Kepert 2006a,b) showed some interesting differences between the storms. The azimuthal mean flow in Hurricane Georges was found to be not supergradient, but that in Mitch was supergradient by 10 m s$^{-1}$ or about 15%. This difference was shown to result from the differing radial structures of the storm. The asymmetric flow in Georges was very similar to that expected from motion forcing; however, Mitch had a similar structure but a different orientation, which was shown to be caused by asymmetric friction resulting from the proximity to land. The analyzed surface wind factors were consistent with the theory in both storms, once account was taken of the different forcing of the asymmetry in Mitch.

These results are similar to those obtained by Schneider and Barnes (2005), who found an anticyclonic rotation of the asymmetries with height for Hurricane Bonnie. They explained the asymmetries as resulting from the close proximity of land, the environmental shear, the organization of convection, and the storm’s translation, but they did not undertake an analysis of flow balance.

The contrasting results in Hurricanes Georges and Mitch point to the need for further analysis to determine how common supergradient flow is in the boundary layer of hurricanes. In addition, there is a need to examine whether the theory delivers equally satisfactory results for less intense storms, which are more common.

The purpose here is to analyze the wind field structure in the boundary layer of Hurricanes Danielle (1998) and Isabel (2003) using high-resolution GPS dropwindsonde data. The idealized modeling studies discussed above have made some potentially important predictions, which can be summarized as follows: (i) The surface-wind factor increases from 0.6–0.7 in the outer core to 0.8–1.0 near the eyewall and is greater on the left side of the storm than on the right (in the Northern Hemisphere); (ii) the jet is more strongly supergradient on the left (right) side in the Northern (Southern) Hemisphere in a moving storm; (iii) the jet is more strongly supergradient near the core than in the cyclone periphery, and the amount of imbalance varies according to the storm intensity and radial wind profile; and (iv) the boundary layer depth increases from around 500 m in the inner core to about 1.5 km at a 100-km radius. These ideas potentially have significant operational impact, but they require further observational verification before this impact can be fully realized. The overall aim of this paper is to provide additional detailed comparisons of theory and observations in two contrasting tropical cyclones.

2. Data and techniques

The analysis techniques and data used in this study are similar to those used by Kepert (2006a,b) and are only briefly summarized here because a full account is contained in those papers.

Two main types of data were used. The GPS dropwindsonde (Hock and Franklin 1999) provided observations of wind speed and direction, pressure, temperature, and humidity at a vertical resolution of approximately 6 m, together with aircraft observations of these variables at the time of launch. The hydrostatic
equation was integrated, with corrections for the radial component of the dropsonde trajectory slope and of the horizontal temperature gradient, to obtain a vertical profile of pressure–height data as described by Kepert (2006a). Aircraft in situ observations of pressure, height, temperature, humidity, and wind (Jorgensen 1984) were also used. For Danielle, these were obtained in storm-relative cylindrical coordinates on a 0.5-km radial grid and were processed back into earth-relative coordinates for this study. For Isabel, instantaneous aircraft measurements at 1-min intervals were used. All data were obtained by research flights of the Hurricane Research Division (HRD) and Aircraft Operations Center (AOC) of the National Oceanic and Atmospheric Administration (NOAA).

The cyclone center location and motion were found by fitting a translating parametric pressure field to aircraft or dropsonde data; that is, by using the translating pressure fit (TPF) method of Kepert (2005). The use of pressure data is particularly advantageous in center-finding in the boundary layer. Wind-based center location algorithms, modified to allow the use of asynoptic data as described in Kepert (2005), were also used as a check. The tracks so found were used for all the coordinate transformations (i.e., earth-relative to storm-relative and cylindrical to Cartesian).

Axisymmetric analyses of the cyclone wind and pressure fields were obtained by nonlinear least squares fitting of the parametric wind profile developed by Willoughby et al. (2006), hereinafter called the WDR profile, in either its wind or pressure forms. The WDR profile may be written as follows:

\[ v_1(r) = (v_{m1} + v_{m2}) (r/r_m)^{n1}, \]
\[ v_2(r) = v_{m1} \exp[(r_m - r)/L_1] + v_{m2} \exp[(r_m - r)/L_2], \]
\[ v(r) = [1 - w(r)] v_1(r) + w(r) v_2(r). \]  

(1)

The profile consists of the weighted mean of an eye profile \(v_1(r)\) with a shape defined by \(n_1 (1 < n_1 < 2)\) and an outer wind profile \(v_2(r)\), which is the sum of two exponentials with length scales \(L_1\) and \(L_2\) and amplitudes \(v_{m1}\) and \(v_{m2}\), respectively. The maximum wind is \(v_m = v_{m1} + v_{m2}\) at the RMW \(r_m\). The weighting function \(w(r)\) is a ninth-order polynomial that increases monotonically from 0 to 1 across a blending zone of width \(2L_b\), containing \(r_m\), with four continuous derivatives at each end of the blending zone. The blending zone is located in radius by requiring that the maximum wind occur at \(r = r_m\), so its location is found by solving \(v'(r_m) = 0\). The pressure form of the WDR profile is found by integrating (1) when substituted into the gradient-wind equation radially with an assumed constant temperature as described by Kepert (2002, appendix 4A.2). The axisymmetric analyses obtained by fitting (1) to the observations are used for the diagnosis of gradient balance and for forcing the numerical boundary layer model of KW01.

It is important in the analysis of gradient balance that the radius of curvature is correctly calculated. One approach to account for the motion of the system is to convert streamline curvature to trajectory curvature using Blaton’s equation (Haltiner and Martin 1957, p. 186). An equivalent and easier alternative is to perform the analysis in a coordinate system moving with the storm. This latter method is strictly valid only if the storm motion is linear because otherwise the transformation into the moving coordinate system will give rise to additional terms in the momentum equations. A similar limitation arises with the use of Blaton’s equation, the derivation of which assumes linear motion. In this paper, all analyses of gradient balance are carried out on the azimuthal wind component in storm-relative coordinates using the physical radius as the radius of curvature. Apart from being mathematically easier, this approach also facilitates comparison with earlier work (Kep01; KW01; Kepert 2006a,b).

Two-dimensional analyses of the horizontal wind field are prepared by a multivariate optimal interpolation technique, using the fitted WDR profile as a background field, with the background error covariances modeled as in Daley (1985, 1991) and with the same covariance model parameter settings as in Kepert (2006a).

The boundary layer flow in these storms is simulated using the numerical model of KW01, which is designed to diagnose the boundary layer flow in response to a prescribed cyclone structure and motion forcing. The domain of this model is only a few kilometers in vertical extent, and that part of the cyclone above the boundary layer is represented by an imposed translating parametric pressure profile at the model’s top boundary. In addition to high vertical and horizontal resolution, this model also features sophisticated turbulence and surface layer parameterizations.

3. Hurricane Danielle

a. Storm synopsis and data coverage

Hurricane Danielle developed out of a tropical wave at the west coast of Africa on 21 August 1998 (Pasch et al. 2001; also see Fig. 1), and reached hurricane intensity on 25 August 1998. From 26 August, the organization of the hurricane began to be disrupted by a south to southeasterly vertical wind shear. During the next few days Danielle weakened, probably both because of the shear and because it moved over water that had
been cooled by the earlier passage of Hurricane Bonnie. By 30 August 1998, Danielle hardly showed hurricane intensity and was moving west-northwest at 9–10 kt. Danielle subsequently recurved and accelerated to the northeast (NE) as it reintensified.

On 30 August 1998, NOAA research aircraft flew two missions into Hurricane Danielle. These were mission 980930I, with a flight level of about 2600 m and a leg length of about 180 km, and 980830H, which was flying an Extended Cyclone Dynamics pattern at an altitude of about 4200 m with 460–550-km-long radial legs. The region from the center to a radial distance about 560 km away was well mapped, with 40 GPS dropsondes in all quarters of the storm. These missions took place at a time when Danielle was in transition from weakening to slow intensification.

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The location of the deployed dropsondes and the flight tracks for both HRD flights can be seen in Fig. 2. The composite radar reflectivity picture (Fig. 3) shows a weakness in the eyewall to the southeast (SE) and a region of very high reflectivity (>47 dBZ) in the northwest (NW) quarter. The main feeder band, composed of many thinner bands, is spiraling into the inner core.

b. Cyclone track

The cyclone track was found from the flight-level data using the methods discussed in Kepert (2005), all of which yielded similar results. The TPF method, which found the storm center at the base time to be located within the Cartesian coordinate system at (−7.1, 3.0) km with a motion of (−1.3, 2.4) m s⁻¹, will be used for the remainder of this analysis. The surface track, using the same method applied to the dropsonde surface pressure data, had a nearly identical motion of (−1.3, 2.7) m s⁻¹ but a base time displacement of (−4.8, 1.1) km. Thus, the storm center has a tilt toward the northwest, from the surface to 2600-m height, of (−2.3, 2.0) km. This tilt is directed a little to the left of the weak vertical shear vector of (−2.6, 0.6) m s⁻¹ toward the northwest; that is, the vortex is tilted downshear-left. The tilt and vertical shear are also consistent with the radar reflectivity asymmetry seen in Fig. 3.

c. Wind field

The radial variation of the boundary layer structure is examined by computing azimuthal means of the ob:

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1 This shear was calculated averaged over a 200–800-km storm-centered annulus, as recommended by DeMaria and Kaplan (1999), using gridded data from the 40-yr European Centre for Medium-Range Weather Forecasts Reanalysis (ERA-40).
served winds. To calculate the mean wind profiles representative of different parts of the storm, the core of Hurricane Danielle was divided into four annular bands, based on the storm structure and the distribution of the dropsondes (see Fig. 2). The resulting groups of sondes are those in the vicinity of the RMW (at a radius of 15–45 km), those in the eye (radius <15 km), those in outer core I (radius 80–130 km), and those in outer core II (radius 130–200 km).

1) ANNULUS-MEAN WIND PROFILES

Vertical profiles for the storm-relative azimuthal and radial wind components $v_{az}$ and $v_{rad}$ for each annulus are shown in Fig. 4. The standard deviation is also shown for bins with more than two soundings. In the eye, the mean wind speed is quite low and nearly constant with height, with almost no evidence of a frictional boundary layer near the surface. The radial wind component shows an overall outflow of about 1–2 m s$^{-1}$ below 1800-m height, consistent with the descending air in the eye. The small step-change in $v_{az}$ near 2.5-km altitude is due to a change in the number of observations.

In the radial band from 15 to 45 km, the maximum mean azimuthal wind is 33 m s$^{-1}$ at approximately 400 m. This inflow layer is about 600 m deep, so the low-level maximum is contained within the inflow layer, and the maximum inflow is almost 10 m s$^{-1}$ and is located near the surface.

In the 80–130-km band, the mean azimuthal wind increases with height up to around 600 m, where the wind maximum of about 26 m s$^{-1}$ occurs. The wind decreases above this height, but not so rapidly as near the RMW. The frictional inflow layer reaches to about 800 m, with the strongest inflow in the lowest 200 m. Above 900 m the inflow is about 1 m s$^{-1}$, which may be an artifact of uneven sampling of the asymmetric inflow or may result from the deep secondary circulation induced by latent heat release described in the review by Willoughby (1995).

In the outermost annulus, the mean azimuthal wind increases with height up to about 1100 m, where it measures about 21 m s$^{-1}$. The wind speed is nearly constant with height above this. The radial wind component shows a frictional inflow layer of similar depth, above which the radial flow is near zero.

In summary, the symmetric structure of flow in this part of the storm is that the boundary layer and inflow layer become shallower toward the storm center, and the low-level maximum becomes more marked. Wherever a low-level maximum occurred in those bands, it was located within and near the top of the frictional inflow layer. This structure is consistent both with theoretical arguments that the depth of the boundary layer varies with the square root of the inertial stability (Rosenthal 1962; Eliassen and Lystad 1977; Kep01; KW01) and with the observational analyses of Kepert (2006a,b). Similar analyses stratified by storm quadrant may be found in Schwendike (2005).

2) HORIZONTAL WIND ANALYSIS

The observed dropsonde horizontal wind components are analyzed at three levels using the statistical interpolation method described by Kepert (2006a). The lowest level of 40 m was chosen to represent the near-surface wind because some GPS sondes failed below this altitude, leaving insufficient data for an analysis. We expect the wind at 40 m to be slightly stronger than the 10-m winds, but the wind speed at this height is still within the logarithmic surface layer (Powell et al. 2003) and the pattern is expected to be similar to that of the 10-m level. The next level of 400 m was chosen because it contains the strongest eyewall winds. The last height of 2000 m represents a typical reconnaissance flight level and is situated above the boundary layer.

The storm-relative horizontal wind analyses are
shown in Fig. 5. The 40-m azimuthal wind analysis (top left) shows a band of wind speeds greater than 30 m s$^{-1}$ extending about halfway around the storm, with two embedded maxima. The main surface maximum is located in the left to left front and rotates slowly to the left with increasing height. The secondary maximum rotates from the right front of the storm near the surface to the right at 2000 m. The radial flow analyses show that the symmetric component of the frictional inflow weakens steadily with height. The asymmetric inflow has two maxima, one to the right and one at the left front of the storm. The former rotates around to the right rear of the storm with increasing height, and the latter remains nearly fixed in position. By 400-m height, relative outflow is apparent in the left rear quadrant of the storm.

The analyzed flow at 2000 m is similar to a deformation field, with the axis of dilation aligned with the storm motion and superimposed on the symmetric vortex. A similar wavenumber-2 pattern was noted in a numerical simulation of Hurricane Bob (1991) by Braun (2002) and attributed to the effects of environmental deformation. Thus, although the reasons for the wavenumber-2 structure in this case are not clear, they may be related to changes in the storm structure as it approaches recurvature. Although this wavenumber-2 pattern clearly influences the analyses at all levels, one can also discern aspects of the idealized simulations of KW01 in the flow, including the maximum inflow in the right front quadrant, the upper boundary layer outflow to the left rear, the surface storm-relative wind maximum to the left front, and the quadrature relationship between the inflow and azimuthal maxima. The maxima in the flow components rotate with height at a rate of roughly 20° km$^{-1}$, which is slower than found by Kepert (2006a,b) in Hurricanes Georges and Mitch, consistent with the lower inertial stability in this weaker storm.

3) WIND REDUCTION FACTOR

To determine the wind reduction factor, the ratios of earth-relative wind speed at 40 m to that at 400 and 2000 m are calculated from the wind analyses and are shown in Fig. 6. For the 40 to 400 m factor, there is a clear left–right asymmetry, with higher values to the left and some suggestion of an increase toward the center. The reduction factor to 40 m from 2000 m shows a more marked increase toward the center, with the asymmet-

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2 The more usual term, surface-wind reduction factor, strictly applies to a “surface” wind at a height of 10 m. To avoid confusion, we adopt the term “wind reduction factor” from Kepert (2006a) here.
Structure consisting of a large area of values exceeding 1 ahead of the storm and a smaller secondary maximum to the rear. The left–right asymmetry and the increase toward the center are similar to the theoretical predictions of KW01 and the analysis by Franklin et al. (2003), although the asymmetry is here oriented more front–back than left–right. Reasons for this difference could include the deformation-related wavenumber 2 pattern already discussed and the northwestward tilt of the vortex axis.

d. Analysis of balance

In this section, the wind and mass fields of Hurricane Danielle and the extent to which the azimuthal mean is in gradient balance are analyzed using the method of Kepert (2006a).

1) Gradient-wind equation I: Pressure analysis

The pressure–height data are used to estimate a radial pressure profile at a range of heights by fitting the pressure form of the WDR profile at various heights to the dropsonde data. The gradient-wind speed is calculated from this pressure curve and compared to the observed storm-relative azimuthal winds. When fitting the WDR profile (1), the parameters \( L_1, r_m, \) and \( L_b \) are held constant at 500, 35, and 10 km, respectively, because otherwise the fitting process becomes ill-conditioned and diverges. The conditions \( n_1 < 2 \) are applied. This analysis is carried out at 100-m intervals from the surface up to 2400 m.

The results of the pressure analysis for 400- and 2000-m heights are shown in Fig. 7. For both altitudes, the pressure and azimuthal wind component observations are shown together with the fitted profiles. It is apparent that the pressure profile fits the observations well; the differences between the observed and fitted pressures were examined and found to be only very weakly correlated with radius within a radius of 40 km from the storm center and not at all correlated in the rest of the storm. Thus, the numerical fitting procedure worked correctly and the pressure gradient was accurately estimated.
The storm-relative azimuthal wind observations in the vicinity of the RMW are slightly supergradient at 400 m (Fig. 7), with a similar imbalance occurring between 200 and 800 m (not shown). This slight imbalance is interesting, but given the observation and analysis error, it is unlikely to be statistically significant. Above 800 m, the flow is analyzed to be balanced as expected, providing confirmation that the analysis scheme is working correctly.

2) GRADIENT-WIND EQUATION II: WIND ANALYSIS

The wind form of the WDR profile is fitted to the dropsonde storm-relative azimuthal wind observations and the gradient-wind equation is integrated inward to compute the gradient pressure profile, which is then compared to the dropsonde pressure–height data. This pressure profile is in good agreement with the observations; thus, the flow is balanced to within the accuracy of the observations and analysis scheme. Because this result is consistent with the other mode of balance analysis, the detailed results are not shown here but may be found in Schwendike (2005).

e. Model simulation

The WDR parametric wind profile (1) is fitted to the flight-level wind observations from flight 980830I and used with the previously analyzed motion to force the model of KW01. The parameters obtained are $u_{m1} = 9.2 \text{ m s}^{-1}$, $L_1 = 30.0 \text{ km}$, $u_{m2} = 24.1 \text{ m s}^{-1}$, $L_2 = 500.0 \text{ km}$, $r_m = 35.0 \text{ km}$, $n_1 = 0.81$ and $L_b = 10 \text{ km}$. The sea surface temperature (SST) was set to 300 K, the environmental pressure to 1010 hPa, and the environmental Brunt–Väisälä frequency to $10^{-3} \text{ s}^{-1}$.

1) DIRECT COMPARISON WITH DROPSONDE-OBSERVED PROFILES

Vertical profiles from the model simulation are compared with dropsonde profiles in the region around the RMW for both wind components in Fig. 8. The model is able to reproduce the strength of the low-level jet relatively well for profiles A, B, C, L, J, and K. The differences between the observed and the computed soundings in profiles D to G are probably due to the vortex tilt of Hurricane Danielle. On 30 August 1998, Danielle moved toward the north-northwest, and we expect the low-level wind maxima to be more peaked toward the left part of the storm, that is, to the west-southwest. The observations are consistent with this, although we caution that part of the strong shear above the low-level maximum in profiles E, F, G, and H is probably due to vortex tilt, which the model does not include.

Profiles D and I show a substantial offset between model and observation at all levels, although the profile...
shape for I is well predicted. These observations were made at a smaller radius than the others were, so this discrepancy may reflect an inaccuracy in the WDR profile used to force the model. A slight misnavigation in the strong gradient may also have contributed. The profiles for dropsondes C and B, D and E, F and G, and I and H are very close to each other, and the first sonde of each pair is located closer to the storm center. The model is generally successful in predicting the difference in the height of the maximum between these pairs of profiles.

The radial wind component is also shown in Fig. 8. It can be seen that the model is generally able to determine the depth of the inflow layer and its variations around the storm. The observations and the model results are in very good agreement for profiles B, C, K, and J: the discrepancies in profiles D–I occur for the same reasons mentioned above.

The modeled azimuthal-mean azimuthal winds are at most only 3% supergradient, consistent with the slightly supergradient flow found in the observation analysis. KW01 and Kepert (2006a,b) have shown that the jet strength is sensitive to storm structure and intensity. Danielle’s structure was not conducive to strongly supergradient flow because of the relative flat wind profiles outside the RMW and the moderate intensity.

2) COMPARISON WITH HORIZONTAL ANALYSES

The modeled horizontal storm-relative azimuthal wind component for the 40-, 400-, and 2000-m heights can be found in Fig. 9. The maximum stormrelative azimuthal wind in the boundary layer occurs in the left front quadrant, and the maximum boundary layer inflow occurs in the right front quadrant, both as found in the observational analysis. Both of these maxima rotate slowly anticyclonically with increasing height. At 2000 m, above the boundary layer, the flow is circular apart from some small-amplitude wavelike features caused by flow instabilities.

The most striking difference to the observational analysis is that it showed a clear azimuthal wavenumber 2 asymmetry that was not reproduced by the model. The model asymmetry is forced by the surface friction asymmetry at wavenumber 1, and higher wavenumbers may arise only through a nonlinear interaction (Shapiro 1983). Although such an interaction is a possibility, these higher wavenumbers have not been seen in other boundary layer observational analyses, and so we be-
FIG. 8. Juxtaposition of profiles of storm-relative (top) azimuthal and (bottom) radial winds observed by dropsondes in the region around the RMW (curves with small-scale fluctuation) and model winds along the same trajectory (smooth curves) in Hurricane Danielle on 30 Aug 1998. The center panels shows the position of the dropsondes as they fell through the 1-km level. The letters denote the different dropsondes; the star represents the storm center.
lieve that an environmental influence is a more likely cause in this case.

f. Summary

The GPS dropsonde and aircraft observations have been analyzed and compared to the results from the numerical model of KW01. The observations show that the inflow layer becomes shallower toward the storm center and that the maximum in the azimuthal wind that occurs in the upper part of the inflow layer becomes more distinct. This low-level azimuthal wind maximum is most marked on the left side of the storm. Additionally, the analysis of the surface-wind factor showed that the largest values occur near the eyewall, and are located in front of the storm near the RMW and on the left side of the storm for larger radii. All these findings are in accordance with the theory.

Although the storm-relative wind speed maximum in the eyewall tends to rotate anticyclonically with height, in accordance with the theory, a wavenumber 2 asymmetry becomes evident above ~400-m height. This feature is absent from theoretical predictions and has not been seen in boundary layer analyses of other storms. We suspect that it may be the response of the storm to some environmental factor such as a deformation field, possibly associated with the impending recurvature of the storm.

The degree of gradient-wind balance has been diagnosed in two ways: first, by comparing the estimated gradient wind from pressure observations to the observed winds, and second, by comparing the estimated gradient pressure field from wind observations to the observed pressure. These analyses showed that the wind in the lowest few kilometers is close to gradient-wind balance, except in the lowest 200 m, where friction causes the winds to be subgradient, and in the layer 200–800 m, where there is weakly supergradient flow near the eyewall.

Quantitative comparison between the model results and the observations showed a similar structure, although the wavenumber 2 asymmetry could not be represented by the model. The model simulation predicted only slightly supergradient flow in the upper boundary layer, consistent with the observation analysis. The soundings in the region around the RMW were directly
compared with the model results and show good agreement between model and observations for the right side and in the north of Hurricane Danielle. The differences between the profiles to the left of the track are probably due to the storm structure, notably the vortex tilt.

4. Hurricane Isabel

Hurricane Isabel (2003) was the most significant tropical cyclone affecting northeastern North Carolina and east-central Virginia since Hurricane Hazel in 1954. Isabel was directly responsible for 16 deaths and indirectly for 34, most of which resulted from the devastating storm surge. Its minimum central pressure of 915 hPa and maximum intensity of about 145 kt occurred at 1800 UTC 11 September 2003. The following analysis is done for 12 September 2003, about 24 h after the maximum intensity and a week before landfall.

a. Storm synopsis and data coverage

Isabel formed out of a tropical wave west of the coast of Africa on 1 September 2003 and subsequently moved slowly westward as it became more organized (Beven and Cobb 2004). Isabel became a tropical depression at 0000 UTC 6 September 2003 and was upgraded to a tropical storm 6 h later. The next day, the storm intensified to hurricane intensity and continued to move west-northwestward while strengthening further (see Fig. 10). On 11 September 2003, the maximum winds reached their peak intensity and Isabel became a category-5 hurricane on the Saffir–Simpson scale. The maximum wind speed remained in the range of 130–140 kt until 15 September, during which time Isabel's eye radius varied within the range of ~30–55 km. During 13–15 September, Isabel turned gradually toward the north-northwest because of a weakness of the western portion of the Azores–Bermuda high. Weakening started on 15 September because of increased vertical shear. Hurricane Isabel made landfall at 1700 UTC 18 September 2003, near Drum Inlet, North Carolina. The highest sustained winds on land amounted to 69 kt, with a gust of 85 kt at an instrumented tower near Cape Hatteras, North Carolina. The weakening of the hurricane proceeded while the storm moved across the United States until Isabel lost its tropical character on 19 September.

The HRD flew 14 missions into Hurricane Isabel. Here, we analyze a dual-aircraft mission on 12 September, comprising flights 20030912H and 20030912I. These flights deployed an unusually high density of dropsondes in the eyewall as part of a special experiment (Black et al. 2007). The storm-relative dropsonde locations and flight tracks are shown in Fig. 11. The flight-level data used are 1-min instantaneous samples that are not organized in radial legs because of the rather unusual mission. The dropsonde and aircraft data are navigated into a Cartesian coordinate system with its origin at the storm center of (20.9°N, 49.4°W), which is the position according to the NHC best track at 1800 UTC 12 September 2003.

A composite radar reflectivity image for 2023 UTC 12 September 2003 (Fig. 12) shows that Hurricane Isabel is a fairly symmetric storm with no prominent rainbands outside of the eyewall. The region of highest reflectivity (>41 dBZ) surrounds the eye like a ring, with an opening to the north. An outer ring of enhanced reflectivity surrounds the eyewall and is strongest to the north. In these images, Hurricane Isabel's eyewall has a radius of about 32 km. There was some variation in the relative strength of these features during the flight, but this variation was not large.

A spectacular set of eyewall mesovortices occurred in the eye at about 1300 UTC 12 September 2003 (Kossin and Schubert 2004), about 3.5 h before the period studied here. A similar set occurred the following day around 1800 UTC (Montgomery et al. 2006). These mesovortices transport momentum into the eye and might be the reason for the expansion of the eye between 12 and 13 September 2003 (Kossin and Eastin 2001). However, it appears that the mesovortices had dissipated by the time of the research missions analyzed here because the radar imagery from the research aircraft (Fig. 12) shows a circular rather than a polygonal eyewall.
b. Cyclone track

The track for Hurricane Isabel was found as described in Kepert (2005), using data from both flights. The track analysis found that the Willoughby–Chelmow track, the simplex track, and the TPF track at a flight level calculated from either flight, as well as the surface track calculated from the dropsonde data by the TPF method, were in close agreement (not shown). All the tracks have a similar motion, but are displaced slightly northward compared to the NHC best track.

Isabel is a symmetric storm and satisfies the assumptions of all these track algorithms. The TPF method at flight level using data from flight 20030912H provides a storm motion of \((-3.96, 0.87)\) m s\(^{-1}\) and a displacement of \((-1.80, 0.86)\) km from the NHC track. The surface track found by applying the TPF method to the dropsonde data is in good agreement with the flight-level TPF track, with a storm motion of \((-4.17, 1.01)\) m s\(^{-1}\) and a displacement of \((-2.19, 0.55)\) km. The difference between the surface and the flight-level tracks indicates a negligible vortex tilt of \((0.39, 0.32)\) km from the surface to 3 km.

c. Wind field

To examine the radial variation of the boundary layer structure, Hurricane Isabel is divided into three annular bands based on the location of the dropsondes (Fig. 11) relative to the RMW. On 12 September 2003, the RMW was approximately 32 km, so the annular bands to be considered are 10–23, 23–32, and 32–48 km. The first two bands represent the region inside the RMW, and the 32–48-km band represents the region outside the RMW.

1) ANNULUS-MEAN WIND STRUCTURE

The mean profiles of storm-relative azimuthal and radial wind are given in Fig. 13. In the innermost annulus, the azimuthal wind reaches its maximum of approximately 60 m s\(^{-1}\) at a height of about 400 m. In the next annulus, immediately inside of the RMW, the maximum wind speed increases to 80 m s\(^{-1}\) at a height of about 600 m. Immediately outside the RMW, the strength of the jet is similar but is located at an altitude of approximately 800 m. Thus, the height of the low-level jet increases with increasing radius. In addition, the shape of the vertical profiles inside and outside the RMW differs above the low-level maximum.
The graphs for the radial wind component show that the inflow layer grows deeper and the inflow strengthens farther away from the storm center. In the 10–23-km annulus, the near-surface inflow layer has a depth of about 700 m, and above that the values are fluctuating around zero. The strongest inflow of about 7 m s\(^{-1}\) occurs in the lowest 200 m of the boundary layer. The maximum inflow reaches a value of approximately 23 m s\(^{-1}\) in the 23–32-km band, and the inflow has a depth of about 600 m. Just outside of the RMW, the inflow layer depth increases up to 900 m, with a maximum inflow of approximately 23 m s\(^{-1}\). Above the inflow layer, there is a deep layer of outflow in the two annuli on either side of the RMW. Note that the low-level jet is near the top of, but within, the inflow layer in each of the three annuli.

2) ASYMMETRIC STRUCTURE

The four quadrants for the 23–32-km radial band are analyzed to examine the asymmetric structure of the boundary layer (Fig. 14). The wind maxima show a clear tendency to be sharper to the right of the storm track (north) than to the left (south). The depth of the inflow layer varies, with deeper inflow to the left of the storm track (~800 m) than to the right (~500 m in the NE and ~400 m in the NW). Above the boundary layer, marked outflow was found in the NE and NW, weak outflow in the southwest (SW), and fluctuations about zero in the SE quadrant. The differences in the magnitude of the mean flow in the various quadrants are due partly to differing radial distributions of the observations within the quadrants and do not necessarily reflect the storm structure.

The results from the 32–48-km annular band, located immediately outside the RMW, are similar to those in the 23–32-km band (not shown). The low-level jet is more marked in the northern quadrants than to the south. In addition, the inflow layer is shallower on the right (northern) side, with a depth of about 800 m, than on the left, where it is about 900 m deep. Outflow can
be found in all quadrants above the inflow layer, but it is stronger to the north.

3) **HORIZONTAL WIND ANALYSES**

Analyses of the horizontal azimuthal and radial wind components, prepared using the same multivariate statistical interpolation scheme as for Hurricane Danielle, are shown at four levels. The “near-surface” wind is represented by the wind at 100-m altitude, which is chosen because of the high dropsonde failure rate below that height. The wind is expected to be stronger at this altitude than at the surface, but 100 m is still within the logarithmic surface layer (Powell et al. 2003) and the overall pattern is expected to be similar to that of the 10-m level. The height of 600 m was chosen as the second level because the strongest winds occur here. The 2000-m level is situated above the boundary layer. Additionally, 300 m was chosen for a better illustration of the changes in the wind structure near the surface.

The storm-relative azimuthal wind (Fig. 15) displays a marked maximum in the left rear quadrant at all levels. This maximum broadens and shows some tendency to split at the 300- and 600-m levels, but this may be an artifact of the data coverage. At 600 m and above, a secondary maximum appears to the right of the track. The radial wind analysis at 100 m shows an inflow maximum in excess of 25 m s\(^{-1}\) to the left front. The overall strength of the frictional inflow decreases away from the surface, but this asymmetry remains fixed in position up to 600 m, above which it weakens. A secondary inflow maximum is apparent to the right rear at the lower three levels.

The left rear location and lack of rotation with height of the main storm-relative azimuthal wind maximum are unusual. The majority of observational analyses have the near-surface storm-relative wind maximum at the left front. The only documented case known to the authors with a similar asymmetry to that found here was described by Hawkins and Imbembo (1976) in their analysis of Hurricane Inez (1966) at 950 hPa. The 850–200-hPa shear vector, calculated from the National Centers for Environmental prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis averaged over a 200–800-km storm-centered annulus, was a 3–5 m s\(^{-1}\) easterly during the observational period. The reflectivity maximum in the eyewall (Fig. 12) in Isabel is thus to the left of the shear vector, as found in many observational and modeling studies. Possibly the weak shear is also causing the unusual wind asymmetry found in the analyses presented here, although why it should dominate the forcing by asymmetric friction is not clear.
4) **Wind Reduction Factor**

The wind reduction factors calculated from the preceding wind analyses, with the winds at 100 m representing the surface wind, are presented in Fig. 16. The largest values at any radius occur in the left to left rear part of the storm, and a clear increase toward the storm center is apparent, as expected both from theory and from the observational analyses of Franklin et al. (2003) and Kepert (2006a,b). The reduction factor is larger from 2000 to 100 m than from 600 to 100 m, consistent with the analysis of Franklin et al. (2003) and with 600 m being near the level of maximum winds in the eyewall.

d. **Analysis of balance**

The gradient-wind balance in Hurricane Isabel is analyzed here in the same manner as done in section 3d for Hurricane Danielle.

1) **Gradient-Wind Equation I: Pressure Analysis**

The pressure form of the WDR profile is used to fit the pressure–height data obtained from hydrostatic integration at every 100 m from the surface to a height of 2 km. The fitted parameters for the WDR parametric profile show a good vertical consistency with height, demonstrating that the curve-fitting is capturing the storm structure well.

The results of the pressure analysis for the heights 600 and 2000 m are presented in Fig. 17, which shows the pressure and the azimuthal wind observations, the fitted pressure profile, and the calculated gradient wind. The pressure residuals were checked and found to be uncorrelated with radius near the RMW, verifying that the gradients are accurately estimated.

The majority of near-eyewall wind observations are substantially greater than the gradient wind; that is, the flow is supergradient. This imbalance exists from ~300 up to 1700 m, and is strongest at 600 m, where the mean storm-relative azimuthal wind is ~10 m s$^{-1}$ stronger than the gradient wind. The wind around the 120-km radius is apparently subgradient over all heights, although given the sparse and asymmetric sampling this is probably an analysis artifact. The eyewall winds are analyzed to be in gradient-wind balance above 1700 m as expected, which provides a consistency check for the analysis.

A Monte Carlo technique is used to examine the statistical significance of the supergradient winds in the vicinity of the RMW. The observations are perturbed with independent normally disturbed random errors.
with a zero mean and standard deviation of 1 hPa, and the curves are refitted. This procedure is done 200 times, and confidence intervals of the gradient wind are determined. The wind observations lie well outside the 95% confidence interval of the gradient-wind envelope between 300 and 1700 m (not shown). Thus, the analyzed imbalance is statistically significant to well in excess of the 95% level.

2) GRADIENT-WIND EQUATION II: WIND ANALYSIS

The WDR wind profile was fitted to the observed storm-relative azimuthal winds every 100 m. The pressure profile was then calculated and compared to the pressure observations. The results (not shown) are that the pressure gradient is too weak to explain the strong winds from 200 up to 1700 m. Hence, the flow is weakly supergradient at 200 m and clearly supergradient from 300 up to 1700 m, with the maximum imbalance at 600 m. Above the boundary layer, the observed pressure distribution is similar to that derived from the wind observations, indicating a return to gradient balance. A similar Monte Carlo technique was used to estimate confidence intervals for this analysis, in which random noise from a normal distribution with zero mean and standard deviation of 5 m s$^{-1}$ was used to perturb the wind observations. The supergradient flow was found to be statistically significant to at least the 95% level. These results are thus fully consistent with the analysis in the preceding section.

e. Model simulation

The WDR profile (1) is fitted to the aircraft wind observations with the following results for flight 20030912H: $v_{m1} = 40.2$ m s$^{-1}$, $L_1 = 65.8$ km, $v_{m2} = 30.0$ m s$^{-1}$, $L_2 = 500.0$ km, $r_m = 33.0$ km, $n_1 = 1.15$, $p_c = 809.7$ hPa, and $L_b = 10$ km. This profile and the analyzed motion are used to force the Kepert and Wang model.

1) VERTICAL STRUCTURE

Radius–height sections of the modeled flow, expressed relative to the gradient-wind speed, are shown in Fig. 18. It is seen that the azimuthal flow is a maximum of 15% supergradient at 400-m height and 25-km radius, just inside of the RMW. This result is in excellent agreement with the analysis of balance in sections 1 and 2. Note also that the model reproduces the observed outflow layer above the azimuthal jet and that the maximum inflow as a proportion of gradient wind is located near 100-m height at a radius of 55 km and amounts to about 35% of the gradient flow there.

The observed and modeled winds are compared in Figs. 19–22. For these comparisons, the model winds are interpolated to the observed storm-relative drop-
sonde trajectories. The winds shown here are averaged over the 23–32- and 32–48-km annuli used in section 4c, subdivided into four quadrants. Comparisons of all of the individual observed profiles with the model were presented in Schwendike (2005).

In the northwest (right front) quadrant (Fig. 19), there is excellent agreement between model and observations, with the only systematic discrepancy being a tendency for the model inflow to be slightly too strong. To the northeast (right rear; Fig. 20), the modeled azimuthal component is 10–15 m s$^{-1}$ too weak through much of the boundary layer, and the observed strong outflow in the upper parts of the profile is largely absent. The general shape of the profiles, however, is well captured. To the southeast (left rear; Fig. 21), the strength of the flow is significantly underpredicted inside of the RMW but is better handled in the outer annulus. The shape of the profiles is again well simulated, although there is a tendency for the modeled height scale to be a little too small. Finally, excellent agreement between model and observations is found to the southwest (left front; Fig. 22), with the only discrepancy being that the model height scales are again slightly too small.

In summary, the model produces a boundary layer structure that is well confirmed by observations. The boundary layer becomes shallower toward the storm center and the azimuthal wind maximum grows more distinct. The level of agreement between the model-simulated mean soundings and the observed mean azimuthal and radial wind profiles is excellent in the west but less successful in the east, where the shape of the profiles is well captured but the model winds are too light. The reason for this discrepancy is not clear, but is likely related to the unusual location of the observed wind speed maximum in the left-rear quadrant.

![Fig. 17. As in Fig. 7, but for Hurricane Isabel for heights of (a) 600 and (b) 2000 m.](image)

![Fig. 18. The model-predicted supergradient flow for Hurricane Isabel: the ratios of the (a) azimuthal and (b) radial wind component to the gradient wind. The contour interval is 0.05; in (a) the heavy line equals 1 and in (b) it equals 0. The white region at 20–30 km radius illustrates 15% supergradient flow.](image)
2) HORIZONTAL STRUCTURE

The horizontal sections of the wind (Fig. 23) are similar to previous calculations with this model. The outward slope of the RMW in the boundary layer with increasing height is apparent, and is clearly frictionally forced because the model does not include a warm core. The azimuthal wind maximum is in the left front near the surface, with the maximum inflow upstream in the right front. Both maxima rotate anticyclonically and weaken with height. As already discussed, this asymmetric structure differs from the behavior seen in the observational analyses. However, these plots further confirm that the model captures the symmetric structure of the storm well, including the strongest winds occurring at about 600 m and the outward slope of the RMW with height. Note that this latter feature is frictionally forced here because the model does not include a warm core.

f. Summary

The wind field of Hurricane Isabel on 12 September 2003 was analyzed, the degree of gradient-wind balance was examined, and the observations were directly compared to the model results. The symmetric structure of the storm is that the boundary layer and the inflow layer become shallower toward the storm center, and the low-level azimuthal wind maximum grows more marked. This low-level jet is located near the top of (but still within) the inflow layer.

Two methods of analyzing the gradient-wind balance showed that the winds in the vicinity of the RMW are supergradient from about 300 up to 1700 m. The largest imbalance, of about 10 m s\(^{-1}\) or 12%, occurred at approximately 600 m. A Monte Carlo analysis demonstrated that the imbalance was statistically significant. The model simulation predicted supergradient flow with very similar characteristics to that obtained from the analysis of balance. Thus, the symmetric structure of Isabel is in strong agreement with the theoretical and modeling predictions of Kep01 and KW01.

In contrast, the asymmetric structure differs from these predictions. The main azimuthal wind maximum is located in the left rear and displays almost no tendency to rotate with height, and a secondary azimuthal wind maximum appears on the right of the storm track.
Fig. 20. As in Fig. 19, but for the NE (right rear) quadrant.

Fig. 21. As in Fig. 19, but for the SE (left rear) quadrant.
above about 600 m. The maximum surface inflow occurred in the left front of the storm and weakened with height. In the model results, the inflow maximum is located in the right front and rotates anticyclonically with height, with the azimuthal wind maximum in the left front. The reasons for the unusual positioning of the flow asymmetries in the observations are not clear; possibly the asymmetric forcing resulting from the relatively slow motion is weaker than that resulting from environmental effects.

5. Discussion and conclusions

The recent advent of the GPS dropsonde has allowed the collection of a wealth of data in the tropical cyclone boundary layer and presented a strong opportunity to fill in a significant gap in our knowledge. At the same time, theoretical and modeling advances have provided an improved framework in which to interpret these data. The main aim of this study has been to analyze the boundary layer wind structure of two contrasting hurricanes using this improved data source.

We analyzed Hurricanes Danielle on 30 August 1998 and Isabel on 12 September 2003. Danielle is a storm of moderate intensity, and Isabel is an intense and fairly symmetric storm. Both hurricanes differ significantly from Hurricanes Georges (1998) and Mitch (1998), analyzed by Kepert (2006a,b). High-resolution GPS dropwindsonde data were analyzed to determine the extent of azimuthal-mean gradient-wind balance in Danielle and Isabel in two different ways, with consistent results in each storm. In Danielle, the flow in the vicinity of the eyewall was found to be subgradient below 300 m, marginally supergradient at 300–800 m, and close to gradient balance above this height. In contrast, strongly supergradient flow occurred in Isabel from about 300–1700 m, with the largest imbalance of 10 m s\(^{-1}\) at about 600 m height and the imbalance being statistically significant throughout the layer. Simulation of the two storms with the boundary layer model of KW01 predicted a supergradient flow of 3% for Danielle and of 15% for Isabel, both of which are in excellent agreement with the observational analyses.

Our results can be related to those of Kepert (2006a,b), who found that Hurricane Mitch showed strongly supergradient flow, whereas Georges did not. This difference was attributed to the contrasting shape of the radial profile of wind in the two storms, and simulation using the model of KW01 was able to reproduce it. Danielle, like Georges, had a relatively flat wind profile and was in addition a less intense storm;
Isabel, however, showed a more peaked radial profile of wind, similar to Mitch. The significance of this difference is that the supergradient flow is produced by inward advection of angular momentum. A storm with a peaked profile has a relatively weak radial gradient of angular momentum except in the vicinity of the eyewall, so there is little opportunity for supergradient flow in such a storm except near the eyewall. In contrast, a storm with a flatter radial profile of gradient wind has a lesser angular momentum gradient but one that extends to large radii, giving weaker but widely distributed supergradient flow. Note also that the peaked-profile storm will, other things being equal, have stronger boundary layer inflow than the flatter case because angular momentum advection is less able to balance its frictional destruction. A more detailed discussion of these dynamics may be found in KW01.

The processes that determine the degree of peakedness of a storm’s wind profile would seem to be worthy of further study because peakedness has a significant impact on the boundary layer wind structure and hence on the expected storm impact. It may also be of interest to analyze the gradient-wind balance on a few successive days of the same storm to study the evolution process of supergradient flow, for instance.

The jet height is expected to decrease toward the center of the cyclone because of the increase in inertial stability toward the center (Rosenthal 1962; Eliassen and Lystad 1977; Keo01). This was confirmed in the present study by calculating the mean wind over several concentric annuli. For Hurricane Danielle, it was found that the height of the jet is about 100 m in the center and increases to 800 m in the outer core. A similar result was found for Isabel: from 10 to 23 km the jet height is about 400 m, from 23 to 32 km it is 600 m, and it is 800 m in the 32–48-km band. The wind was found to increase approximately with the logarithm of the height below the low-level jet, consistent with Franklin et al. (2003) and Powell et al. (2003), and to decrease above the wind maximum. There are two reasons for this decrease: first, the cyclone warm core produces a decrease in the gradient-wind speed with height as described by the thermal wind equation, and second, in Isabel the wind returns from being markedly supergradient to gradient. Although Franklin et al. (2003) attributed this decrease to only the warm core, we have
presented further convincing evidence that flow imbalance is a strong contributor in storms with peaked radial profiles of wind.

In both storms, the asymmetries around the RMW were at variance with theoretical predictions and with analyses of other storms. The near-surface flow in Danielle was similar to predictions, but a marked wave-number 2 pattern occurred in and above the upper boundary layer. In Isabel, the near-surface storm-relative azimuthal wind maximum was unusually located in the left rear quadrant and showed little tendency to rotate with height, although a secondary maximum appeared to the right of the storm away from the surface. It is likely in both cases that the environment is responsible for these unusual patterns, possibly in the form of deformation for Danielle and vertical shear for Isabel. The relatively slow motion of both storms means that the frictional asymmetric forcing would have been relatively weak, allowing other influences to dominate.

The wind reduction factor (i.e., the ratio of a near-surface wind speed to that at some reference level aloft) increases toward the storm center for both storms and displays a tendency for higher values on the left of the track than the right, consistent with the predictions of Kep01 and the observational analysis of Franklin et al. (2003).

The boundary layer flow in the two storms was simulated using the numerical model of KW01, forced by the fitted pressure profiles and storm motions. Although the model results are in only fair agreement with individual dropsonde profiles, prediction of larger-scale features was more successful. In particular, the radial variation in the boundary layer depth, the degree of supergradient flow, and the spatial variation of the near-surface wind factor are well depicted. Environmental shear and concomitant vortex tilt seem to be the main reason for the deviations between the model results and the individual observations in Hurricane Danielle. The reasons in Isabel are not as clear but are perhaps related to environmental shear.

This study has provided further evidence for the substantial variability in boundary layer structure in tropical cyclones, both within and between storms. A substantial part of this structure, notably the variation with radius and the relative strength of the near-surface winds, is predictable by simplified models. Prediction of the variation with azimuth is less successful but by no means without skill, with the absence of environmental shear and the consequent vortex tilt being perhaps the main omission from such models. In the cases analyzed here, the relatively slow movement and consequently weak asymmetric friction forcing helped other processes to dominate. However, the idealized models appear to have sufficient realism to be usable for operational estimation of surface winds in situations for which there is sufficient data to determine the structure of the storm in enough detail. Such testing would also provide an opportunity to further validate the models.

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