Estimation of the Surface Stress in the Eye-wall Environment of Hurricanes using WSR-88D Radar Data

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1. Introduction

Analysis of Doppler velocity data from the WSR-88D radar during hurricane landfall reveals evidence of organized secondary circulations in the hurricane eye-wall environment at low elevations. The Velocity-Azimuth Display (VAD) method is applied to the radar data to obtain mean wind profiles (Browning and Wexler 1968). The mean wind profiles are analyzed for hurricane inflow layer and boundary layer depth. A residual or anomaly velocity field is obtained by subtracting the VAD velocity (first harmonic) from the radial velocity for elevation angles between 0.5 and 5.5 degrees (Fig. 1). The wavelength, depth, magnitude, and motion of velocity anomalies are then compiled from the residual velocity displays, with reference to VAD mean wind profiles. The resulting statistics provide compelling evidence for the presence of organized secondary circulations or boundary layer rolls in hurricanes (e.g., Etling and Brown, 1993).

Evidence of secondary circulations in the boundary layer (BL) has been documented through Doppler radar analysis. Kelly (1982), using data from a single Doppler radar, found an alternating pattern of diffluence and confluence in the Doppler velocity fields associated with BL rolls. Christian and Wakimoto (1989) related BL rolls to cloud street location in light wind conditions using single Doppler radar data. They found BL roll convergence areas caused radar echoes aligned with the cloud streets. Wurman and Winslow (1998) analyzed Doppler on Wheels data gathered during Hurricane Fran (1996). They showed the wind field in the lowest 200 m included features that resemble BL rolls aligned along the mean wind vector. These features were small, narrow regions of enhanced flow flanked by large horizontal gradients (10^{-1} s^{-1}). Variations in the surface wind field associated with BL rolls in hurricanes will produce significant gradients in dissipative heating (Businger and Businger 2000) that may feed back positively on the circulation of the rolls.

Glendening (1996) examines a large eddy simulation (LES) of a marine BL under strong shear and low buoyancy conditions. The LES produced BL rolls that transported significant amounts of momentum, moisture, and heat vertically. Brown and Zeng (2001) compare a two-layer similarity planetary boundary layer model to GPS dropsonde observations in a hurricane environment. The BL model includes a parameterization of the BL roll effects on wind profile, momentum, and heat fluxes. They show the BL model matches the GPS dropsonde observations well, and this favorable comparison is

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due to the inclusion of the nonlinear BL roll effects. Currently, most numerical weather prediction (NWP) planetary BL models do not employ BL roll effects in the transport of momentum, heat, and moisture. Instead, they use an eddy-viscosity model that parameterizes the turbulent transport homogeneously throughout the BL.

In this paper we compile statistics associated with the signatures of BL rolls in WSR-88D data. The goals of this work are to improve our understanding of the hurricane boundary layer, which will lead to improved parameterization of surface energy fluxes in numerical models of hurricanes and improved analysis of the variations of the surface wind field associated with hurricane eye walls. The implications of the results for momentum and heat fluxes in the hurricane boundary layer are discussed.

2. Methods

The WSR-88D radar completes a volume scan in 6 minutes when scanning in precipitation-mode. The volume scan is composed of fourteen 360˚ scans at elevation angles ranging from 0.5° -19.5°. A Fourier analysis of the Velocity-Azimuth Display (VAD) is used to estimate volume divergence (0th harmonic), profiles of mean wind speed and direction (1st harmonic), and mean deformation (2nd harmonic) (Browning and Wexler 1968). At a given scan elevation, mean radial velocity (1st harmonic) is a sinusoidal function of azimuth angle, with the amplitude and phase of the sine curve providing the mean wind speed and direction (Fig. 1).

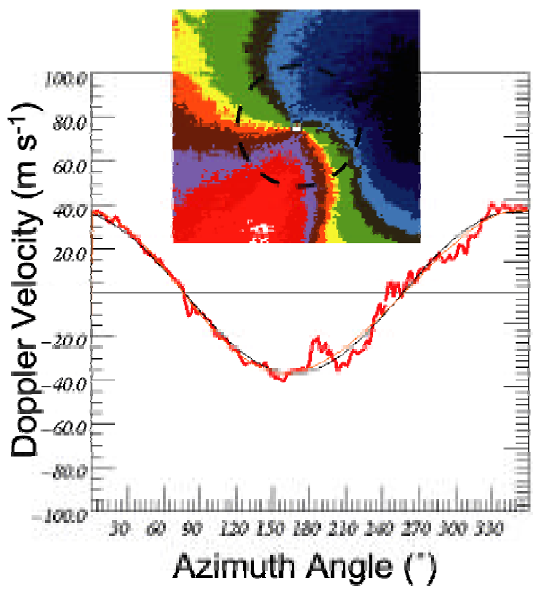

Fig. 1 Example VAD display of WSR-88D Doppler velocity (Vr) (red line), and mean radial velocity (sinusoidal black line).

Mean wind profiles are derived through application of the VAD method to the Doppler velocities at each elevation angle out to a radius of 10.7 km (Browning and Wexler 1968) (Fig. 2). VAD wind profiles have been compared to profiles from operational radiosonde balloons released in close proximity to the radar site (Fig. 3). The tangential wind profiles from the VAD method and radiosondes are in

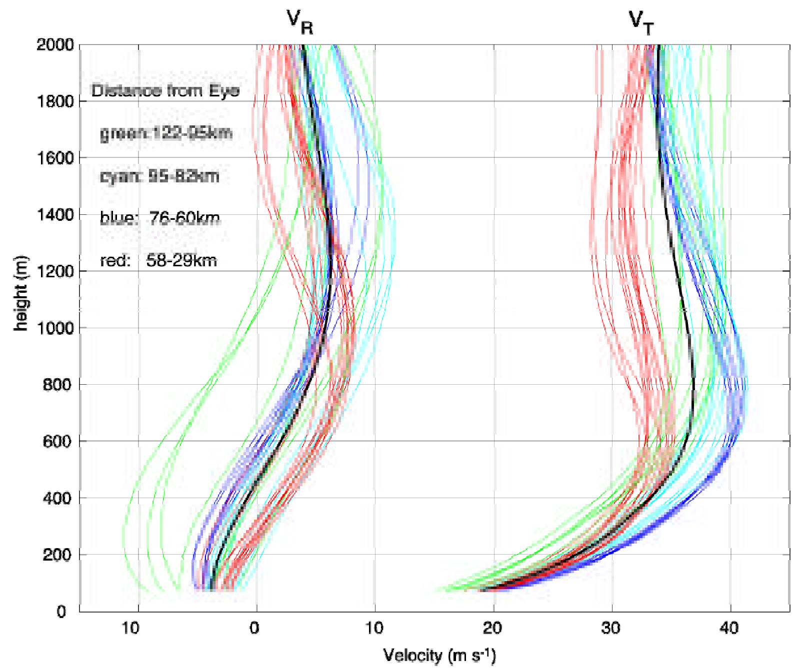

Fig 2 VAD tangential (V_T) and radial (V_R) wind profiles in hurricane Bonnie at distances from 29 to 122 km from the eye (see color code above). The heavy black line is the mean of the component VAD wind profiles taken in Bonnie.

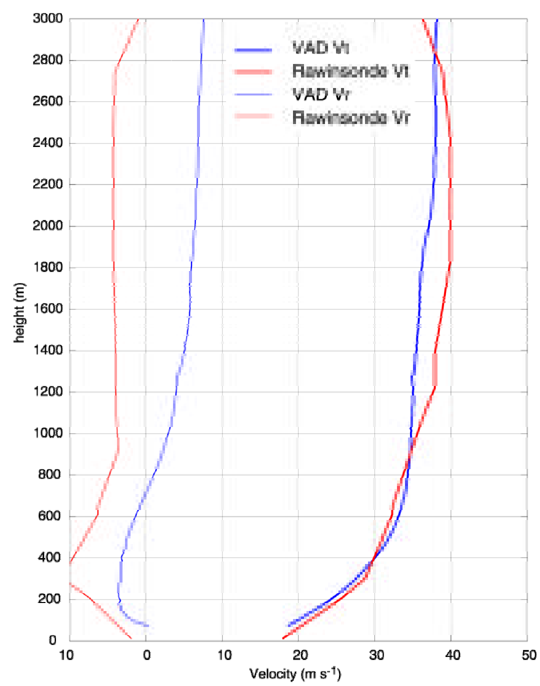

Fig. 3 Comparison of tangential and radial wind profiles as measured by radiosonde and the VAD method. The radiosonde was released in Morehead City, NC at 0000 UTC on 8 August 1998, 114 km from center of Hurricane Bonnie.

good agreement, whereas the radial velocity differences are greater (5-10 ms^{-1}). These differences can be explained in part by noting that Vr varies substantially with radial distance to the eye, moreover as an areal average, the VAD derived Vr is sensitive to the proximity of the hurricane eye (Fig. 2).

To isolate the pattern of BL rolls from the mean background flow, the VAD velocity (1st harmonic) is subtracted from the radial velocity to produce a residual (anomaly) velocity field (Fig 4). Adjacent pairs of positive and negative residual velocity anomalies provide evidence of BL rolls (Fig. 5). The wavelength, average height, intensity, and motion of the BL rolls can be estimated from the residual velocity field given the location and elevation of the radar site. Elevation angles only up to 5.5° are used to keep the beam within the boundary layer out to a horizontal range of ~10 km. To be included in the statistical analysis of the BL roll signatures the following criteria must be met (i) identified residual anomaly pairs must be within 15° of the mean wind direction, (ii) the magnitude of the residual velocity values must be ≥ 3 $m\ s^{-1}$, and (iii) the pairs must be identified in at least two consecutive 360˚ scans.

The depth of the BL roll circulation can be estimated with reference to VAD mean wind profiles (Fig. 6). Assuming that the vertical circulation associated with the BL rolls is transferring momentum in the vertical, the heights where the mean wind profile matches the positive and negative wind anomalies are used to estimate the depth of the BL roll circulation.

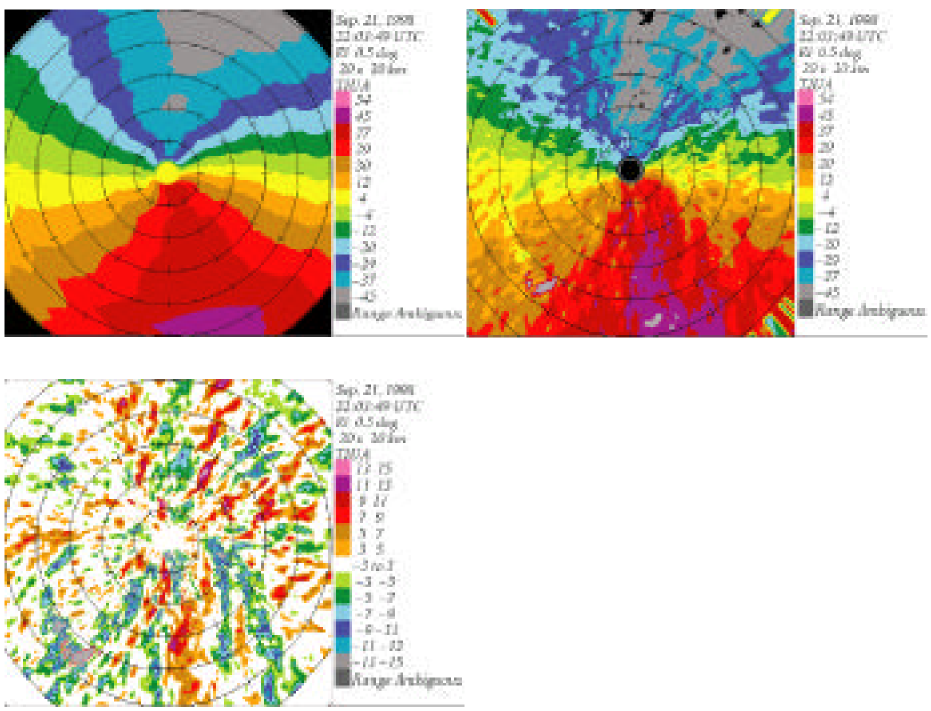

Fig. 4 The Doppler residual velocity field is calculated by subtracting (a) the mean Doppler velocity from (b) the Doppler velocity to get (c) the residual (anomaly) velocity field. Data shown are from the Puerto Rico WSR-88D at 2203 UTC on 21 September 1998, taken in Hurricane Georges.

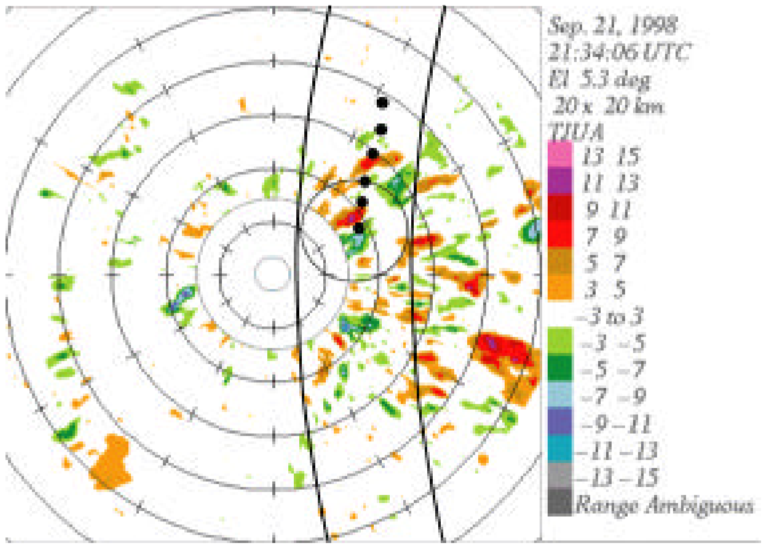

Fig. 5 Track of an anomalous residual velocity pair (small dots). The heavy black lines are rings of constant radial distance from the eye, and approximate the orientation of local isobars. The eye of hurricane Georges is 30 km due east, e.g., to the right of the diagram, at 21:34 UTC on 21 September 1998.

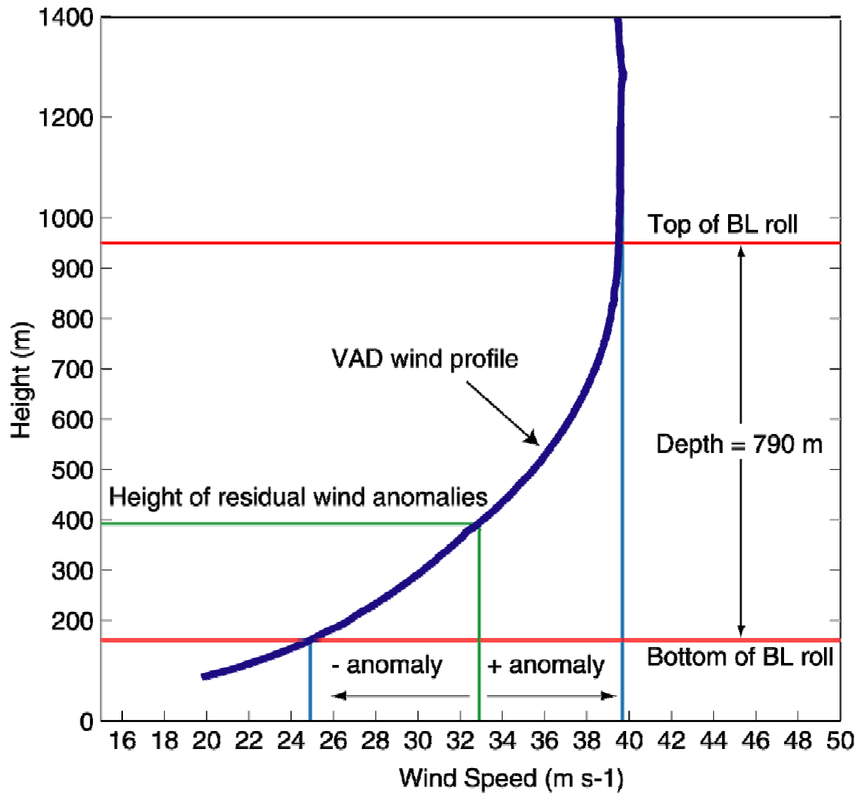

Fig. 6 Illustration of the method used to estimate the BL roll depth from the VAD profile and the characteristics of the BL roll. The data shown are for a BL roll observed in Hurricane Bonnie at 0425 UTC, 27 August 1998.

3. Results and Discussion

To date, three storms have been examined, Fran (1996), Bonnie (1998), and Georges (1998), using WSR-88D data from Wilmington, N.C., Morehead City, N.C., Puerto Rico, and Key West, FL, respectively. The analysis focuses on the time period between the first identified BL roll and hurricane landfall. Fran was a category 3 hurricane approaching North Carolina and dropped to a category 2 near landfall. Fran passed within 28 km of Wilmington and the first BL rolls were identified 105 km from the eye. Bonnie was a category 1 to 2 during the sampling period and passed within 30 km from Morehead City. The first BL rolls were identified when Bonnie passed within 120 km of Morehead City. Georges passed 25 km from Key West as a category 2 storm and BL rolls were identified to a distance of 80 km from the eye.

The inflection point in the tangential wind (V_T) profiles, where the curvature goes from positive to negative, provides a depth estimate of the hurricane BL (Brown 1980). For hurricane Bonnie the BL depth varies from ~800 to 1200 m, with estimates of the depth of the BL roll circulations, which average 660 m. The depth of the hurricane inflow layer can be inferred by examining profiles of the mean radial wind component (V_R). For hurricane Bonnie the depth of the inflow layer ranges from <200 m to >1100 m, with a mean inflow depth of ~450 m. These data suggest that the inflow layer depth is slightly less than the depth of the BL rolls and the depth of the BL.

There is a wide range of aspect ratios for BL rolls found in the literature (Etling and Brown, 1993). From observation using satellite, radar, lidar, tower, and aircraft, aspects ratios range from 2 to 12 with most common values between 4 and 6. The aspect ratio, defined as the BL wavelength divided by depth, ranges from 1 to 4.5 km for all the cases, with a mean of 2.37 (Fig. 7). The aspect ratio data show a general increase in variability with distance away from the eye wall. Figure 8 shows the results of the analysis of 142 BL-roll signatures associated with the four hurricane landfalls. The wavelength ranges from 800 m to 3000 m, and the depth from 350 m to 1300 m.

Linear theory predicts an aspect ratio of ~2. The BL rolls create positive and negative residual velocities side by side that result in substantial vorticity values across the BL roll (~0.011 s^{-1}). The BL rolls identified in the residual velocity field move with the mean wind. Analysis of BL roll motion suggests that the tracks curve with the gradient wind, moving roughly parallel to inferred isobars (Fig. 5).

The BL rolls transport high momentum air from the top of the BL downward towards the surface (see schematic in Fig. 9), producing enhanced winds at the surface. These locally enhanced winds result in anomalous dissipative heating (Businger and Businger 2000) and an increased production of sea spray. In combination these circumstances result in a locally enhanced latent heat flux and increased buoyancy of air, which is then entrained into the updraft region of the BL roll. This overall process enhances the energy transport in the BL and increases the efficiency of the ocean-atmosphere energy flux.

Current research efforts include estimation of the momentum fluxes associated with the secondary circulations through application of mixing length theory. Estimates of the surface stress will be obtained from the radar derived wind profiles using a modified momentum budget approach. We are working to apply the Large Eddy Simulation model in an effort to simulate the observations. The goal of these efforts is to determine the impact of secondary circulations on the magnitude of the surface stress in the hurricane eye-wall environment and to contrast the results with other approaches for estimating the stress.

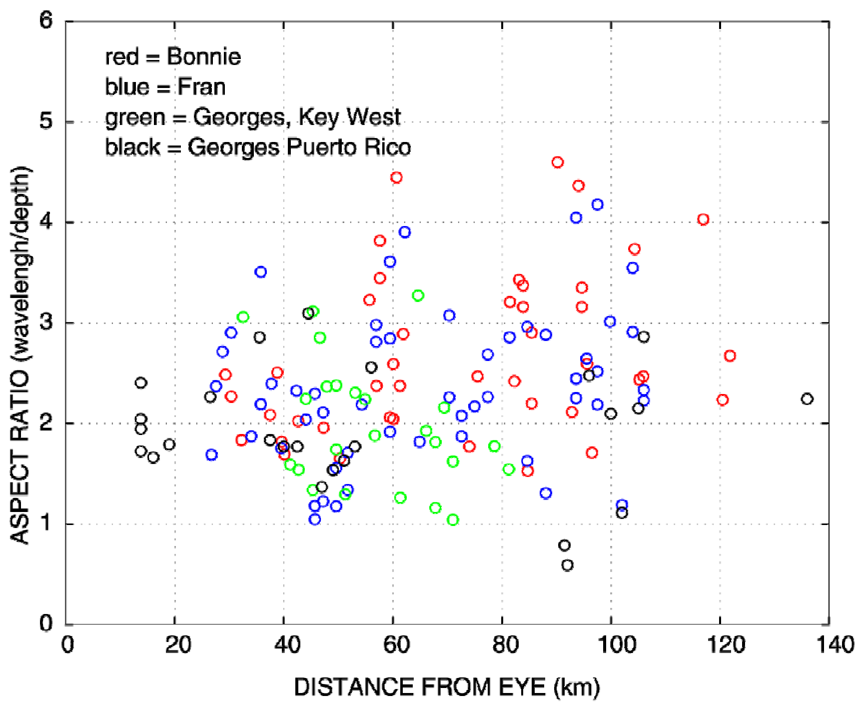

Fig. 7 Distribution of the aspect ratios (width/depth) of 142 BL rolls in four hurricane landfalls.

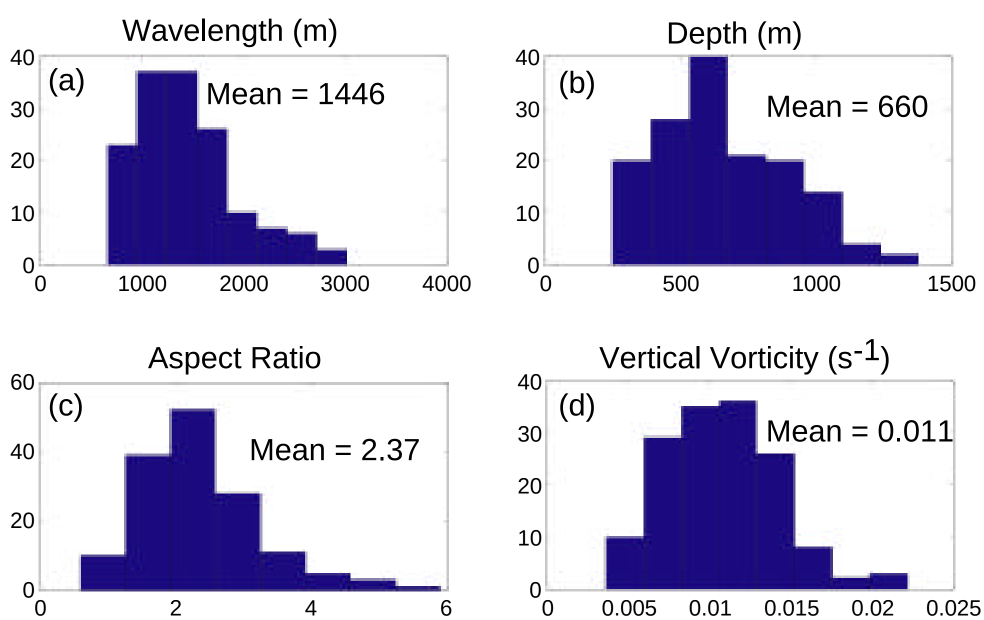

Fig. 8 Histograms of (a) wavelength, (b) depth, (c) aspect ratio and (d) vertical vorticity for 142 BL rolls observed during four hurricane landfalls.

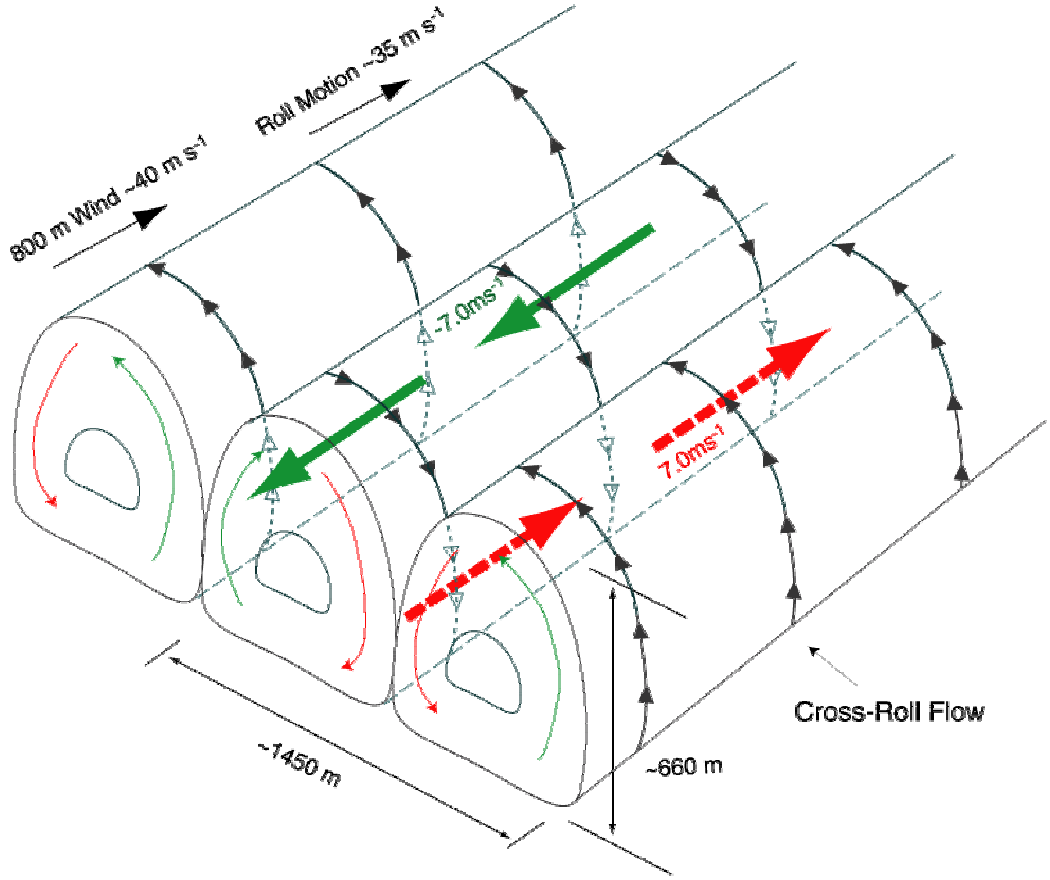

Fig. 9 Schematic depicting hurricane boundary layer rolls, showing the mean values for 142 BL rolls observed during four hurricane landfalls (142 cases). Thin red (green) arrows indicate high (low) momentum air being transported downward (upward). Heavy red and green arrows indicate the positive (negative) residual velocity captured by the WSR-88D. The wind speed (40 m s^{-1}) and direction in the boundary layer at 800 m and mean motion (35 m s^{-1}) of the rolls are indicated at the top of the schematic.

4. References

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