Finescale Spiral Band Features within a Numerical Simulation of Hurricane Opal (1995)

GLEN S. ROMINE
University of Illinois at Urbana–Champaign, Urbana, Illinois

ROBERT B. WILHELMSON
University of Illinois at Urbana–Champaign, and the National Center for Supercomputing Applications, Urbana, Illinois

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ABSTRACT

One of the most recognizable features associated with a well-organized tropical system are spiral rainbands. These quasi-stationary rainbands often extend hundreds of kilometers from the storm center and have been well described in the literature. Observational studies have since identified additional banding structures, including outward-propagating small-scale spiral bands. These rainbands may have considerable implications for “core type” tornadoes, local wind maxima associated with downburst damage swaths, as well as a role in overall hurricane dynamics. As such, here a numerical simulation of Hurricane Opal (1995) is examined with unprecedented resolution necessary to capture these small-scale spiral bands. Opal was an intense landfalling hurricane that demonstrated small-scale spiral banding features analogous to those observational studies. The scale and characteristics of the simulated bands are consistent with observed small-scale spiral banding of intense hurricanes. A varietal of Kelvin–Helmholtz instability combined with boundary layer shear is offered as the most plausible dynamical mechanism for the generation and maintenance of these propagating bands outward of the eyewall region.

1. Introduction

Hurricanes possess well-defined structural components including an eye, eyewall, and numerous rainbands. Recently, hurricane observations suggest a further commonality among many intense systems—small-scale spiral banding features. These small-scale bands appear most prevalent within the core region and propagate outward, unlike the quasi-stationary and spatially larger hurricane rainbands. Because wind circulations associated with these bands can produce enhanced surface winds, understanding them may offer further insight into the damage potential of hurricanes at landfall. Interestingly, once developed, these bands appear to be maintained within hurricanes that have significantly weakened, suggesting that the history of hurricane intensity is an important characteristic in forecasting wind damage potential at landfall. Owing to the significant economic and social impacts of landfalling hurricanes, further understanding of small-scale band structure and behavior is warranted.

Small-scale spiral bands may impact hurricane dynamics across several scales of motion. On the larger end, it has been suggested that circulations associated with banded precipitation (not necessarily just the small-scale spiral bands) could lead to the inward flux of energy and outward flux of momentum (e.g., Willeoughby 1977; Guinn and Schubert 1993). Further, small-scale bands may also contribute to local modification of the hurricane wind field within the surface layer, leading to local enhancement of wind speed and subsequent increase in regional wind damage potential. Wakimoto and Black (1994) provided a detailed analysis of the damage associated with the landfall of Hurricane Andrew (1992). They found sharp gradients in wind damage across distances of just a few kilometers. In addition, tornadoes are another frequent hazard associated with landfalling hurricanes and can occur in the core or outer rainbands (McCaul 1991). McCaul noted that core tornadoes typically occur during the day of landfall in strong, well-organized hurricanes and...
Several hypotheses have been proposed for the organization of rainbands of varying scales within hurricanes and in other settings. A brief review and their potential for explaining small-scale bands are shown in Table 1. Inertia-buoyancy waves were proposed by Kurihara (1976), Willoughby (1977), and Willoughby (1978) and Rayleigh instability was proposed by Fung (1977). GTH98 suggested a deep boundary layer roll analogy while Wurman and Winslow (1998) also described a boundary layer roll phenomena observed by mobile Doppler radar during the landfall of Hurricane Fran (1996), and Nolan (2005) provided an idealized study capturing two scales of boundary layer instabilities. Potential vorticity waves (aka vortex Rossby edge waves) have also been suggested as a forcing mechanism for outward-propagating spiral rainbands (e.g., Guinn and Schubert 1993; Montgomery and Kallenbach 1997). Specifically, Montgomery and Kallenbach (1997) offered outward-propagating vortex Rossby waves as a mechanism for the small-scale banding de-
scribed by GTH98,1 in spite of a recognized mismatch in scale and wavenumber. Further, a numerical study by Chen and Yau (2001) of Hurricane Andrew further described spiral rainbands forced by potential vorticity anomalies with band characteristics similar to those described by Montgomery and Kallenbach (1997). An observational study utilizing airborne dual-Doppler data from a weakening Hurricane Olivia by Reasor et al. (2000) further supports the idea of vortex Rossby wave shedding, but their focus was on a wavenumber-2 disturbance, dissimilar to the bands described in GTH98.

Numerical simulations of hurricanes using primitive equation models with high resolution offer an opportunity to further elucidate the dynamics of these small-scale band features and determine their cause. In fact, GTH98 suggested these bands should be apparent in numerical simulations of hurricanes of sufficient spatial resolution (~1 km) provided the simulation utilized realistic parameterizations. Several recent numerical studies of hurricanes have embraced the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) as a useful tool for investigating hurricane dynamics (e.g., Liu et al. 1997, 1999; Zhang et al. 2000, 2001, 2002) and have provided considerable insight into the behavior and structure of these systems. In addition, very high spatial resolution simulations (e.g., Davis and Bosart 2001, 2002; Braun and Tao 2000; Braun 2002) are now approaching 1-km horizontal spatial resolution. However, these latter very high spatial resolution simulations are not of strong hurricanes, and GTH98 suggested intensity was a key factor in the presence of small-scale spiral bands in observed hurricanes.

Our study describes a very high spatial resolution simulation of Hurricane Opal (1995). Opal is one of the most studied hurricanes in the literature, often with emphasis on the unique rapid intensification episode (e.g., Krishnamurti et al. 1998; Bender and Ginis 2000; Bosart et al. 2000; Shapiro and Möller 2003). However, our interest here centers on simulated and observed banding features with similar structure and behavior to those described by GTH98 as Opal approached the Florida coast. A description of the numerical model is followed by a discussion of the banding features within the simulation and how they compare with the observed bands. Then, a dynamical mechanism is proposed for observed band features based on the results from the simulation. Finally, a discussion is provided on possible implications of band circulations and their intersections on the development of core tornadoes and severe convective scale downbursts as well as possible implications for broader hurricane dynamics.

2. Methodology

Numerical simulations of Hurricane Opal were conducted using the MM5. The model initial state was interpolated from the European Centre for Medium-Range Weather Forecasts (ECMWF) 147 × 37 2.5°-resolution Tropical Ocean and Global Atmosphere (TOGA) analysis from 0000 UTC 2 October 1995. Similar analyses were also employed for boundary conditions from the initial state time through 0000 UTC 7 October 1995. Sea surface temperatures were extracted from the National Meteorological Center (NMC) analysis for the initial time and held fixed.

The modeling methodology employed for this work is based on the ensemble simulations reported by Ramamurthy (1999). In particular, the physical parameterizations chosen follow from coarse-resolution tests by Romine and Wilhelmson (2001) of a subset of the most realistic ensemble members in Ramamurthy (1999). Multiple nest levels were used to achieve cloud-resolving horizontal resolution. The initial and boundary condition fields were first interpolated to an outer 90-km grid. Four two-way nested grids were then applied successively with 30-, 10-, 3.3-, and 1.1-km resolution as shown in Fig. 1. The size and placement of the nested grid domains were set so that the simulated hurricane remained well within each of the domains over the length of the simulation. For the first 48 h, only the outer two domains were active. Domain 3 was then added at 48 h followed by domain 4 at 60 h. Finally, the 1.1-km grid simulation began at 76 h and moved within domain 4 to follow the hurricane as shown in Fig. 1b. In the vertical, 35 layers were utilized between the surface and 70 mb, with significantly increased resolution in the lowest few kilometers. The time step for the coarse domain was set at 180 s, leading to an innermost grid time step of 2.22 s.

Model parameterization choices included the use of the Betts–Miller–Janić cumulus parameterization for the outer three grids along with Reisner mixed-phase explicit microphysics for all grids. The Blackadar boundary layer scheme was used in all domains. Nudging of the wind and temperature fields to the analysis fields was utilized for the first 24 h on the outer grid only in order to capture the initial sharp clockwise turn of Opal to the northeast. The Community Climate Model version 2 (CCM2) radiation scheme, five-layer soil model, and shallow convection scheme were some of the other key physics options chosen for the simulation.

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1 This study referred to Tuttle and Gall (1995), which provided an early description of the results later published in GTH98 and included analysis of Hurricanes Andrew and Hugo only.
The model initial state at 0000 UTC 2 October 1995 was synoptically favorable for the development of an intense hurricane. A longwave trough covered most of the western United States, with a broad upper-level ridge from the Mid-Atlantic states extending into the Gulf of Mexico. The model contained a weak tropical cyclone with a 996-mb low pressure center in the Bay of Campeche, 11 mb higher than the observed Tropical Storm Opal at that time. The upper-level ridge supported good outflow. Weak deep-layer shear was present throughout the Gulf and combined with a warm and deep ocean surface layer that produced an environment favorable for hurricane development. The maximum potential intensity model from Emanuel (1999) suggests Opal would be capable of a minimum central pressure of 890 mb assuming a mean tropopause temperature of 193 K (Rodgers et al. 1998).

The model initial state for the tropical system possessed a weak warm core along with a deep vortex, but the mass and momentum fields in the core were misaligned with each other, especially at 500 mb in the analysis fields. The surface pressure minima and circulation center were also misaligned, and this inconsistency extended upward through the depth of the system. These errors in the analysis fields likely contribute to the initial simulated track errors as noted by M. Ramamurthy (2001, personal communication), and were partially corrected by the aforementioned nudging of the temperature and wind fields. The choice to use fixed sea surface temperatures from the initial state time was necessitated by the lag in the simulated hurricane track relative to the observed system.

Despite the coarsely defined initial state, a weaker-than-observed disturbance within the Bay of Campeche develops into a category 5 hurricane (slightly more intense than the observed Opal, which only reached strong category 4 intensity) within the simulation having a track (Fig. 2a) and intensity (Fig. 2b) similar to the observed event. The simulated hurricane retained its deep low pressure for considerably longer than the observed storm with a delayed landfall. As shown in Fig. 3, the precipitation distribution becomes increasingly asymmetric with a wavenumber-1 pattern in the precipitation distribution favoring the northwest quadrant relative to the hurricane motion. This orientation is typical in numerical simulations of hurricanes with moist physics, as further described by Braun (2002) and as observed with Opal after landfall. Romine and Wilhelmson (2002) also described the convective characteristics of the outer rainband environment relative to the observed event, which was well captured. Overall, the model simulation compares favorably with the observed track and intensity along with the precipitation distribution and characteristics.

Fig. 1. Grid layouts for the Hurricane Opal simulation: (a) outer four grids; (b) mobile innermost high-resolution grid relative to domain 4. The mobile inner nest moves from its “initial” box position at 76 h to its “final” box position at 94 h following the motion of the hurricane (heavy dashed line).
3. Diagnostics of the simulated spiral bands

a. Simulated spiral band characteristics

A 5-h analysis of the finescale spiral banding within the Opal simulation is focused on the model fields from the highest-resolution grid beginning at 84.6 h into the integration. At this time, the simulated Opal is positioned about 225 km south-southeast of Pensacola, Florida, with a minimum central pressure of 921 mb and peak winds to 60 m s\(^{-1}\), while tracking slowly northeast at 2.5 m s\(^{-1}\). This analysis time period was chosen owing to the steady-state intensity and greater symmetry within the simulated storm relative to later periods. Further, this allows for more direct comparison to the GTH98 cases, which all demonstrated greater symmetry. The surface tangential and radial mean wind profiles are given in Fig. 4a. Peak tangential winds of 36 m s\(^{-1}\) are at a radius of 45 km, while peak radial inflow of 22 m s\(^{-1}\) is 20 km farther away from the center. Mean radial profiles of maximum perturbation temperature and vertical velocity are shown in Fig. 4b with core temperatures exceeding 10 K relative to the outer mean environment and a broad vertical velocity maxima along and just inward of the radius of maximum winds associated with outward-sloping eyewall ascent. Notably, considerable variance is present in the vertical velocity field (not shown), with peak updrafts to 18 m s\(^{-1}\) largely within the eyewall.

The simulation also reveals a finescale spiral-banded structure, particularly in the wind field within the lowest few kilometers. This is illustrated in Fig. 5a where the absolute vertical vorticity structure at 1 km AGL is shown. Analysis of full 3D vorticity reveals that this banded structure is characterized by thin, horizontally elongated vortex sheets around the hurricane center out to 100 km in radius (not shown). As seen in the figure, the azimuthal band length varies substantially from 10 to over 100 km. The radial spacing between bands varies from 8 to 15 km with bands intersecting intermittently, particularly near the hurricane center. Banding features with similar spatial characteristics are also evident in horizontal cross sections of cloud water (Fig. 5b) and vertical velocity (Fig. 5c), as well as equivalent potential temperature (Fig. 5d). It is also notable that numerous “hot towers” are evident along the left edge of the hurricane eyewall relative to the system’s motion vector. These are similar to those recently described by Braun (2002), but display a strong tendency here to concentrate in a wavenumber-1 pattern. The lack of cloud water within the northwest quadrant of the hurricane owes to efficient scavenging of cloud water by widespread intense precipitation (Fig. 3a).

The bands are further characterized by significant variations in azimuthal and radial wind speed. This is shown in vertical cross sections along the direction of motion outward of the eyewall in Figs. 6a and 6b, respectively, spatially averaged by 10 km either side of a line along the axis indicated in Fig. 5c. The cross-sectional axis is nearly aligned with the hurricane’s motion such that it lies approximately normal to the mean band axis. Variations in wind speed are periodic and

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Fig. 2. (a) Simulated (observed) track through 94 (84) h from 0000 UTC 2 Oct 1995 shown by the solid (dashed) line within domain 2. (b) Simulated (observed) intensity versus time through 90 h from 0000 UTC 2 Oct 1995 with circles (squares) at 6-h intervals. Landfall is noted by the short solid vertical lines.
have spacing slightly less than 10 km near the hurricane center with modest increasing scale along the radial leg up to 15 km at 100 km away from the hurricane eye. The modeled bands cross slightly inward of concentric circles (i.e., they “spiral inward”) centered on the hurricane eye as one moves cyclonically. The horizontal vorticity, which dominates the enstrophy (absolute magnitude of the curl of the 3D velocity vector) field, is generally large in the near-surface hurricane environment owing to considerable vertical shear of the horizontal winds at low levels (Fig. 7). Asymmetry in the enstrophy field correlates with the vertical circulation enhancement from buoyant acceleration. At the suggestion of a reviewer, latent heat release was disabled for a short restart period, resulting in a reduction in depth and intensity of the band circulations, but with little change in horizontal spacing (not shown). When the horizontal vorticity is overlain with bands of alternating ascent and descent, this sheet of horizontal vorticity is perturbed, leading to tilting and generation of
the vertical vorticity pattern shown in Figs. 5a and 6e. Furthermore, deep ascent is generally associated with minima in rainwater content, whereas descent is associated with relative maxima such that updrafts lie just radially inward of precipitation bands (Figs. 6c and 6d). Finally, a similar spatial-banding pattern is also present in contours of equivalent potential temperature, especially within the lowest few kilometers (Fig. 6f).

The bands are also evident in other scalar variables (not shown) such as potential temperature and all water species. Although detailed stability analysis from only one time period from the simulation is shown, features are temporally persistent and animations of the above-mentioned fields show consistent spatial patterns associated with slow outward band motion when viewed along a fixed radial leg. This is demonstrated in the spatial and temporal persistence of the banding pattern as maxima in the mean enstrophy within the lowest 500 m of the model domain (Figs. 7 and 8). Band intensity, as inferred from the magnitude of enstrophy, is notably asymmetrically distributed about the hurricane center, yet is temporally consistent in magnitude and character despite considerable changes in hurricane intensity during this period, filling at a rate slightly over 2 mb h\(^{-1}\). A band-normal radial leg leading the hurricane track was constructed, extending from the inner eyewall edge outward 100 km over a 3-h period beginning at 85.5 h, in order to generate Hovmöller diagrams from cross sections of perturbation radar reflectivity (Fig. 9) and upward vertical velocity (Fig. 10) at 2 km AGL. Noise is apparent in these fields owing at least in part to convection and superimposed wave interactions at this resolution (not shown). However, comparisons of spatial patterns of enhanced enstrophy along the indicated cross section in Fig. 8 with higher values of vertical velocity (Fig. 10) and positive perturbation radar reflectivity (Fig. 9) shows a banding pattern, labeled A–H in Figs. 8 and 9, linking the three fields. Animation over the 3-h period demonstrates continuous outward band propagation with a phase speed of near 10 m s\(^{-1}\) (Figs. 9 and 10). This phase speed appears relatively constant with range, despite marked differences in the radial and azimuthal flow with radius (Fig. 4a). Enhanced perturbation radar reflectivity is generally just radially outward of enhanced vertical velocity, as was previously shown in Figs. 6e and 6d. Further, a range of Fourier harmonics from 5 to 8 for the 100-km-wide window (Fig. 10) is consistent with a typical band spacing of 12–16 km (Fig. 11).

Even though the horizontal distribution of precipitation for Opal (both simulated and especially observed) is more asymmetric than the cases described in GTH98, investigation of the radar data still showed small-scale spiral banding patterns consistent with their study. By example, a representative radar reflectivity base scan is shown in Fig. 12 as Hurricane Opal approached the Florida coast. The reflectivity plot is subjectively overlain with dashed lines highlighting the small-scale spiral band axes as positive perturbations in the radar reflectivity field. Reconstructed range–height indicator plots demonstrated a mean band height from 4 to 6 km (not shown), consistent with the vertical extent noted in GTH98. Bands are spaced somewhat closer together near the hurricane eye than well away from it, extending up to 100 km out from the hurricane center with a mean across-band spacing of 12 km. In summary, the
Fig. 5. Horizontal cross sections centered over the hurricane center at 84.6 h into the simulation on the 1.1-km grid. Contours shown are of (a) cyclonic vertical vorticity at 0.001 s⁻¹ intervals, (b) cloud water every 0.25 g kg⁻¹, and (c) upward vertical velocity every 1 m s⁻¹, all at 1 km AGL, along with (d) equivalent potential temperature every 1.5 K beginning from 354 K at 0.5 km AGL, the latter with darker shading indicating higher values. The heavy line on Fig. 5c marks the axis of the vertical cross sections shown in Fig. 6.

Fig. 6. Vertical cross sections from 0 to 6 km in height AGL along the axis indicated in Fig. 5c relative to the hurricane position at 84.6 h into the simulation on the 1.1-km grid. Contours shown are of relative (a) azimuthal wind speed and (b) radial wind speed overlain with wind speed contours every 5 m s⁻¹, where darker shading indicates higher magnitudes and plots are overlain with circulation vectors in the cross-section plane, and a storm motion of 2.1 m s⁻¹ from 225° is subtracted. Also shown are contours of (c) vertical velocity every 100 cm s⁻¹ (negative regions dashed and shaded), (d) precipitation in g kg⁻¹ (shaded regions indicate larger magnitudes), (e) vertical vorticity in 10⁻⁵ s⁻¹ contoured every 0.001 s⁻¹ (negative regions shaded), and (f) equivalent potential temperature every 1 K.
Fig. 7. (a)–(f) Contours of mean enstrophy every $10^{-2} \, \text{s}^{-1}$ within the lowest 500 m every hour from 85 to 90 h.
depth, width, length, and propagation appear qualitatively similar to both the bands described in GTH98 and with the simulated Opal bands.

b. Assessment of possible banding mechanisms using model data

As shown in Table 1, there are a number of possible mechanisms described in the literature for the organization of rainbands in hurricanes or that may be applicable to rainbands in hurricane environments. Some are better supported than others are by the results of the Opal simulation. As such, comparisons are subcategorized into supported and unsupported mechanisms below.

1) Supported banding mechanisms

Among the mechanisms listed in Table 1, Kelvin–Helmholtz instability (KHI) can occur in flow regimes
with weak static stability and large vertical shear gradients, resulting in breaking waves that can subsequently lead to convective triggering and internal gravity waves (e.g., Weckwerth and Wakimoto 1992). Testud et al. (1980) observed banded precipitation structures near a frontal zone with strong cross-frontal shear noting parallel, banded structures with spatial separations of $\approx 10$ km and a phase velocity of $\approx 5$ m s$^{-1}$, quite similar to the band phase and spacing noted in GTH98. However, in the case presented by Testud et al. (1980), bands were aligned perpendicular to the mean shear, while within the hurricane environment observed small-scale bands are aligned nearly parallel to the mean shear vector. Yet, Lilly (1966) detailed how the stability of the Ekman boundary layer flow can lead to parallel bands typically aligned $20^\circ$ left of the geostrophic wind vector. Applying this to a gradient wind balance more appropriate for a hurricane environment, spiral-banding patterns crossing counterclockwise of concentric rings would then be predicted. Essentially, within the hurricane environment the strong tangential winds perpendicular to the radial shear instability axis (azimuthal flow field) can contribute to a stable organization of this vertical mixing process, similar to the Beltrami-type flows described by Lilly (1986) as the horizontal vorticity and velocity vectors within the azimuthal jet cores align, manifesting the wave fronts into long, organized, horizontal roll vortices.

Consideration of the local Richardson number (Stull 1988), which represents the ratio of buoyant suppression to shear generation of turbulence, provides further attribution of KHI to the banding mechanism. KHI develops in regions where the local Richardson number is less than one-fourth, though it can be maintained by values greater than that once instability has already developed (Stull 1988). Dry Richardson number calculations for the radial inflow, shown in Fig. 13a, confirm the surface layer shear and stability are more than adequate for the production of KHI within the lowest kilometer, which roughly coincides with the depth of the surface radial inflow layer. The vertical shear gradient within the radial outflow layer is not sufficiently strong to expect KHI to develop or be maintained, except within the eyewall itself. The inclusion of moist physics significantly complicates the scenario, as some regions are convectively unstable, particularly within the ascending branches of the roll circulations (Fig. 13b). Notably, it is evident that the moist outflow layer may have some enhanced instability by the inclusion of moist static stability criteria.

Typically, KHI generates waves that are evanescent and as such fail to match the outward-directed phase velocity observed by GTH98. However, Lalas and Einaudi (1976) described several KHI-generated gravity wave modes within extreme shear conditions near a ground surface. In particular, their mode III waves, with a critical Richardson number of 0.14, propagated above the shear layer. Testud et al. (1980) found this mode adequate to describe the propagating band structures from their study. Applying the same methodology, the Lalas and Einaudi (1976) characteristics were calculated for the case of the Opal simulation. Using the mean characteristics of the environment within 30 km of the eyewall from the cross section shown in Fig. 6, the approximate phase speed and characteristic wavelength are 6 m s$^{-1}$ and 8.8 km, respectively. These values are similar to the characteristics of the bands in the Opal simulation within the inner-core region.

Franklin et al. (2003) demonstrated that peak winds in hurricanes exist closer to the surface than previously accepted with average peak horizontal winds only 500–750 m AGL. KHI may have not been seriously considered prior to this study owing to limited knowledge of actual near-surface shear characteristics, along with the apparent discrepancy in alignment relative to the mean shear vector.

Although the inertia-buoyancy wave modes proposed in Kurihara (1976) and Willoughby (1977, 1978) were larger than the observed small-scale bands, they still could serve to explain some aspects of the observed band behavior if generated by the KHI mechanism described above. Gravity waves inherently generate ver-
tical mixing within dynamically unstable shear layers and hence could lead to the small-scale spiral band patterns. Following Lindzen and Tung (1976), the idealized flow field and resultant thermal perturbations normal to a gravity wave front result in wind and potential temperature fields in quadrature, that is, with a 90° phase shift between the wavelike perturbation fields. This gravity wave signature should be present in the numerical simulation if gravity waves are responsible for the small-scale banding. There is a clear pattern of convergence and divergence, as well as wavelike perturbations in the potential temperature and equivalent potential temperature fields in the simulation (Fig. 14). Interestingly, the phase shift is not in quadrature along with a pattern of convergence/divergence extending through the boundary layer within 30 km of the eyewall (Fig. 14a), yet moving radially outward along the same cross section another pattern emerges atop the boundary layer that more closely resembles a gravity wave signature (Fig. 14b). It is then suggested that a continuous instability mechanism must be present to drive the periodic flow field but that gravity waves may emerge outside of the region where the banding appears to be forced.

A further check for gravity wave propagation as a fit for the finescale wave features was carried out. In the simulation, the estimated wavelength (~10 km) of a potential gravity wave was calculated using model output. The Brunt–Väisälä frequency for the top of the boundary layer radial inflow, where peak winds reside, possessed a mean value of $1.7 \times 10^{-5}$ s$^{-2}$, which if converted to a period yields ~4 min. The wind speed at the top of the boundary layer in the peak radial inflow of ~30 m s$^{-1}$ then translates to a gravity wave horizon-

Fig. 13. Same as Fig. 6f, except contours of (a) dry and (b) moist Richardson number (dimensionless) using radial wind component, where shaded regions are less than 0.25, with contours every 0.25 to 1.0, along with circulation vectors in the plane and contours of equivalent potential temperature (dashed). Also, (c) Scorer parameter contours in the lowest 3 km of the same cross section, with contours every 0.25 km$^2$ and (d) potential vorticity where shaded regions are greater than 5 PVU and contours of rainwater every 0.5 g kg$^{-1}$.
terrestrial wavelength of \( \sim 7.3 \) km, slightly smaller than the mean wavelength both in the simulation and observational studies. Continuing to yield to the possibility that gravity waves could at least partially explain the banding phenomena, it is worthwhile to consider if the environment within the simulation would favor their maintenance. Gravity wave ducts, in their dry form, have been the subject of several studies including their role in severe windstorms along the lee of the Rockies (e.g., Klemp and Lilly 1978) and with amplification and maintenance of large-amplitude gravity waves (e.g., Ramamurthy et al. 1993). The gravity wave duct efficiency is maximized if the duct depth is one-quarter of the vertical wavelength of the gravity wave (Lindzen and Tung 1976). This is related to the reflection of upward-propagating gravity waves by the overlying neutral layer, which then propagates back downward through the underlying stable layer, arriving in phase with the original gravity wave. Hence constructive wave interaction results, with amplification of the magnitude of the original gravity wave disturbance.

Two distinct layers stable to moist processes by parcel theory are present in the Opal simulation. The first is near the surface, where despite considerable surface boundary sensible and latent heating, a shallow moist process inversion is present through the inner eyewall as shown in Fig. 6f. The depth of this inversion decreases as one moves radially inward toward the hurricane eye; hence, the vertical stability becomes increasingly neutral. Above this stable layer, a 3–5-km-deep neutral layer for moist processes exists, which extends through a greater depth as one moves radially outward from the hurricane center bounded by another stable layer, associated with the latent heated radial exhaust from eyewall convection. The moist neutral layer, trapped between these two stable layers, is well mixed in momentum and could act as a reflector for an underlying gravity wave if present. Therefore, the simulated hurricane environment could potentially serve as host for moist process gravity wave activity, which in turn could offer a dynamical description of the finescale banding phenomena in the outer-core region. The Scorer parameter (Scorer 1949) offers additional insight into the likelihood of gravity waves. After subtracting the hurricane motion vector from the radial wind profile, the ratio of the Brunt–Väisälä frequency to wind shear minus the velocity profile curvature is shown in Fig. 13c. Where the Scorer parameter decreases rapidly with increasing height, trapped gravity waves are favored. This is noted to occur along the top of the boundary layer interface, with increasing height radially outward. The magnitude of the Scorer parameter can also be used to determine the preferred wavelength, where the resonant wavenumber lies between the square root of the upper and lower Scorer parameter values across the interface. Using the magnitudes shown in Fig. 10c, this yields a range of horizontal wavelengths from 5 to 9 km, which are generally smaller than the observed values. It is suggested then that the environment is at least favorable for sustained

![Cross sections of radial convergence (dark shading) and divergence (light shading) greater than 0.001 s\(^{-1}\), potential temperature (short dashed), equivalent potential temperature (solid), and circulation vectors in the plane. Cross section is from the same time and location as was shown in Fig. 6, except it is split where (a) is the inner half and (b) is the outermost segment.](image-url)
gravity waves at a scale similar yet generally smaller than the observed bands.

2) Unsupported banding mechanisms

A number of potential banding mechanisms from Table 1 were not supported by our simulation results or greatly differed from the observed small-scale band characteristics. These include the inward-propagating inertia-buoyancy wave modes and those with greater than 20-km wavelengths, as well as the diminutive boundary layer rolls described by Wurman and Winslow (1998). Additionally, the Rayleigh instability proposed by Fung (1977) also differs substantially from the observed small-scale band characteristics in both horizontal scale and negligible outward phase speed. GTH98 suggested a deep boundary layer roll analogy, which the instability associated with the Ekman layer (Lilly 1966) could potentially support. However, a propagation mechanism is lacking along with the improbable near-constant phase speed with radius given the azimuthal wind profile (Fig. 4a).

More plausibly, moist symmetric instability can arise under saturated conditions in the presence of weak moist static stability, large vertical shear, and anticyclonic horizontal wind shear. The associated time scale would be several hours and resulting convection slantwise. Symmetric instability has been proposed as playing a significant role in eyewall convection (e.g., Emanuel 1986; Braun 2002). Moreover, the slantwise convection is consistent with an outward-sloping eyewall, as is frequently observed (e.g., Marks and Houze 1987). A simple test for symmetric instability follows from comparing the ratio of Coriolis force to the vertical component of absolute vorticity with the critical Richardson number. Where this ratio is less than the local Richardson number, symmetric instability is favored. Further, symmetric instability requires that the environment be baroclinic, which is marginally met within the boundary layer inflow. Combined, these conditions are satisfied where regions of positive stability are collocated with negative absolute vertical vorticity. Analysis of the Opal simulation reveals that only the eyewall region provides an agreeable setting for symmetric instability (not shown), similar to the findings of Braun (2002). Elsewhere the simulation possesses a state of moist slantwise neutrality with absolute momentum surfaces being nearly parallel to equivalent potential temperature surfaces, and wave front normal flow is not along equivalent potential temperature surfaces outside the eyewall itself (e.g., Fig. 13). Regions of negative absolute vorticity (shown in Fig. 6e, shaded) where symmetric instability is possible are generally confined to the surface layer. Following parcel trajectories along the inflow, cyclonic vertical vorticity is present with parcels ascending equivalent potential temperature surfaces, while anticyclonic vertical vorticity is present along descending surfaces. Plainly, vertical vorticity present in the surface layer is dominated by the tilting of horizontal shear into the vertical. Since virtual potential temperature surfaces are nearly coincidental with slopes of absolute momentum surfaces, slantwise neutral motions do not appear appropriate for describing the small-scale banding that extends well beyond the eyewall region.

Finally, potential vorticity anomalies associated with the shedding of vortex Rossby edge waves from the large potential vorticity source in the hurricane eyewall has been suggested. In particular, Chen and Yau (2001) investigated the role of vortex Rossby waves in a numerical study of Hurricane Andrew (1992). After demonstrating cloud and potential vorticity bands were strongly coupled in their case study, they suggested potential vorticity dynamics were essential for the formation and behavior of small-scale spiral rainbands. While they noted that the small-scale banding features noted in GTH98 could be explained by vortex Rossby wave shedding, the 6-km horizontal resolution in their study was inadequate to resolve the 10-km horizontal wavelength disturbance described by GTH98. As such, their study is inconclusive with regard to the origin of the observed small-scale spiral-banding pattern. Investigation of the Hurricane Opal simulation does reveal potential vorticity anomalies within the surface layer and within the overlying stable outflow layer. However, as apparent from Fig. 13d, many potential vorticity bands are disbursed throughout the model domain, and most are at best indirectly associated with precipitation bands. That said, small potential vorticity anomalies are collocated with cyclonic vertical vorticity anomalies (e.g., Fig. 6e) in the surface inflow layer, but as previously shown, these are most likely produced from tilting (not shedding from the eye). Some clustering may be present within the potential vorticity field in Fig. 13d, such as between 20–30 km and again from 50–60 km, which would have a spacing more typical of the Rossby edge waves described by Montgomery and Kallenbach (1997). In conclusion, the role of potential vorticity anomalies in the finescale hurricane bands within the simulation is unclear and is a topic requiring further investigation.

4. Discussion

a. Proposed explanation

No single explanation for the finescale-banded structure appears to be sufficient. However, based on the
analysis, we believe the dominant mechanism for the finescale banding pattern shown in this model simulation results from a fusion of mechanisms as follows. The roll vortices stably organize within the considerable tangential flow, similar to a Beltrami-type flow field (Lilly 1966) with generally conserved momentum at their cores. The large radial gradient of vertical shear in the surface inflow layer leads to the development of an outward propagating Kelvin–Helmholtz-type instability. In particular, within the region of peak radial inflow outward of the eyewall, the KHI mode III instability of Lalas and Einaudi (1976) is favored when the inflow strength is sufficient to meet the shear criteria. For the Opal simulation, this region lies within about 30 km of the hurricane eyewall at the analysis time. The resulting flow field oscillations generated by the instability cause vertical displacements within a moist process stable layer, mixing higher momentum air toward the surface and higher equivalent potential temperature air upward in a nearly saturated process within the core region of the mature hurricane. Ascending branches of the circulation beyond the surface layer are enhanced via buoyant accelerations owing to latent heat release in a conditionally unstable environment, whereas bands are limited to the height of the boundary layer depth elsewhere. The ascending branches of the roll circulation are marked by locally greater vertical ascent, increased condensate concentrations, and higher values of equivalent potential temperature. These properties are consistent with the radar observations of GTH98 as well as the in situ observations of Willoughby et al. (1984).

b. Banding evolution and impacts at landfall

Enhancement of banding features occurs in the simulation as the hurricane approaches land despite significant weakening of the hurricane’s intensity during this period. So, despite reduction in wind speeds near the ground owing to increased friction from sea to land, vertical shear (horizontal vorticity) in the simulation increases as near-surface winds slow more rapidly than winds aloft. This is reflected in the vertical shear profiles of the simulation as the hurricane winds move farther inland. Enhanced banding features include intensification of the near-surface vertical circulation following the enhancement in vertical shear and more vigorous overturning owing to shearing instability. This subsequently results in considerable increases in vertical vorticity magnitudes in the surface layer through tilting of the extreme magnitude of horizontal vorticity, concentrated through horizontal convergence where bands intersect, which in the simulation appears most often in the left-front quadrant relative to the hurricane’s motion vector. For example, Fig. 15 illustrates the vertical vorticity and vertical velocity fields from the Opal simulation an hour and a half after landfall to the north of the hurricane’s eye. A notable axis of enhanced cyclonic curvature is evident in these fields, indicated by the dashed line, with elevated field values immediately downwind, highlighting a region that might favor tornado cyclone-scale circulations on the left side of the shearing axis where convergence is maximized at the intersection of bands.

McCaul (1991) suggested core tornadoes were more prevalent with intense landfalling storms. He further noted that the history of intensity was a factor, where hurricanes that had previously been more intense were more likely to produce tornadoes at landfall. As such, it is hypothesized that convergent small-scale band circulations may enhance core tornado embryos. The preference within the simulation for these convergence points to occur along and to the immediate left of the hurricane track agrees quite well with the relative location of many of the reported core tornadoes that occurred during the landfall of Hurricane Opal. Recall from Fig. 12 that the observations also showed several intersection points of bands, particularly near the hurricane track.

Descending branches of the circulations associated with the banding aid transport of higher momentum air
toward the surface where peak winds are a mere 500 m AGL throughout much of the core region. The down-
ward transport of momentum can result in periodic sig-
nificant surface wind gusts as is commonly observed
within individual squalls during hurricane landfalls, in-
cluding Opal (Powell and Houston 1998). Dropsonde
profiles from Franklin et al. (2003) noted an apparent
shift in downward momentum transport efficiency as
maximum winds at the top of the boundary layer ex-
cceeded 70 m s\(^{-1}\). While the sample size for extreme
events in their study was small, the shift could follow
from the onset of vertical circulations associated with
small-scale bands as the shear criteria for KHI is met.
Additionally, near-surface vertical motion can aid in
the production of low-level vertical vorticity via tilting
of low-level vertical wind shear with cyclonic vertical
vorticity equivalent to a supercell thunderstorm meso-
cyclone circulation (as high as 0.01 s\(^{-1}\)) within the Opal
simulation. If the relation between band intersections
and core tornado occurrences can be verified, it could
significantly aid forecasters in assessing the tornadic
threat of hurricanes at landfall based on banded reflec-
tivity patterns. As such, further exploration is war-
ranted both through numerical and detailed observa-
tional studies.

c. Further considerations

Despite the relative sophistication of the MM5
model, there are shortcomings with its ability to accu-
rately represent the hurricane environment. Most no-
tably, the air–sea interface is poorly handled and this
likely plays a critical role in the storm’s development
(Emanuel 1995). There are neither flux contributions
from sea spray (a source of latent and sensible heat
flux), nor significant surface wind drag associated with
waves (which must consume a modest amount of mo-
mentum). Additionally, the model does not account for
the cooling surface ocean waters as turbulent mixing of
the ocean surface layer takes place. Fortunately, the
latter is not as serious for this case because of the pres-
ence of a warm core ring in the Gulf of Mexico well
described by Shay et al. (2000). Errors due to an over-
simplified turbulence closure scheme within the MM5
also limit the resolving ability of the model at fine reso-
lutions. The vertical resolution used in our study may
also have been inadequate to properly represent the
horizontal scales of the gravity waves (e.g., Lindzen and
Fox-Rabinovitz 1989), perhaps related to the apparent
slightly larger horizontal scales within the simulation
relative to the observations and anticipated values from
analysis. It is also possible some of the model physics
shortcomings may to some degree cancel each other out
sufficiently so that there is still a reasonable approxi-
mation to the appropriate fluxes for the air–sea inter-
face exchange. This is at least suggested by the fact that
the Opal simulation reasonably approximates the ob-
served peak intensity despite all the above-noted weak-
nesses.

A key remaining research question to address is why
only hurricanes achieving category 2 intensity or higher
illustrate banding features like those seen in Opal and
the GTH98 study. The answer may relate to the pro-
posed instability mechanism. While the shear threshold
for initiating the propagating mode of KHI is quite
high, once KHI has developed a lower threshold is suf-
ficient to maintain the instability. Further, an additional
scale of motion likely underlies the finest scales repre-
sented here; such as the boundary layer roll phenomena
observed by Wurman and Winslow (1998), which may
play an additive roll through upscale growth. A recent
idealized numerical study by Nolan (2005) extends sup-
port for a distinct separation in scales between bound-
ary layer streaks and the larger small-scale bands. How
these circulations interact will likely need to be ad-
ressed within a full physics model of ultrahigh resolu-
tion to better understand the complex hurricane bound-
ary layer.

5. Summary

Analysis of the numerical simulation of Opal reveals
a finescale spiral-banding pattern consistent with the
scale and characteristics of the observed small-scale spi-
ral banding of intense hurricanes. Through analysis of
model output and qualitative comparison with observa-
tional studies, it is shown that the generation of fine-
scale banding features within the hurricane core region
evolves from a special Kelvin–Helmholtz-type instabil-
ity within the hurricane boundary layer upon reaching a
critical magnitude of vertical shear within the radial
inflow. In the analysis period of the Opal simulation,
this development is favored in the region of peak radial
inflow within 30 km of the eyewall. The phase and
wavelength of the observed and simulated bands favors
the KHI mechanism among those considered, though
gravity waves and boundary layer rolls appear integral
in a total description. Further, the importance of hur-
cricane intensity in small-scale banding development
agrees with a critical inflow threshold to commence
KHI and subsequent banding, as well as the subsequent
maintenance as the criteria is lessened following initia-
tion. The cross-band circulations significantly influence
the vertical transport of heat and moisture, aiding
transport of high equivalent potential temperature air
within the surface inflow layer upward. Although a
near moist-adiabatic environment, this lifting is suffi-
cient to result in modest buoyancy owing to latent heat release within the ascending branches of the roll vortices that further aids in parcel ascent and enhanced precipitation that is revealed as bands in intense hurricanes. In the presence of a moist potentially unstable environment, the vertical extent of the ascending branch of the roll circulation appears to be largely limited by the height of the base of the outflow layer where buoyant parcels reach their equilibrium level. Finally, banding is also evident within the core region outside of where moist processes are occurring, but with limited vertical extent and intensity.

These banded circulations may play a significant role in transporting angular momentum inward toward the hurricane core that would tie these bands to the regulation of hurricane intensity. Further, descending branches of roll circulations aid in downward momentum transport, and coupled with convergent band circulations, may favor increased wind damage potential with historically intense hurricanes. These potential impacts warrant further investigation. Analysis of finescale banding within this simulation offers a theory for the dynamical mechanism responsible for their presence. The implications for these bands could be considerable, from local phenomena such as core tornadoes and severe wind gust events up to hurricane momentum and heat flux regulation. Future work will hopefully shed light on some of these remaining research questions. Limitations in spatial and temporal resolution of current observations limit our ability to validate mechanisms for this and other hurricane cases. However, more detailed observations of hurricane structure are likely to become available in the future, which could be used to evaluate our hypothesis of band formation.

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REFERENCES


