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ABSTRACT

This study examines spiral rainbands in a numerical simulation of Hurricane Bill (2009). This paper, the first part of the study, evaluates the structures of spiral rainbands and compares them to previous observations. Four types of spiral rainbands are identified: principal, secondary, distant, and inner rainbands. Principal rainbands tend to be stationary relative to the storm center, while secondary rainbands are more transient and move around the storm center. Both principal and secondary rainbands are tilted radially outward with height and have many of the commonly observed kinematic features, such as overturning secondary circulation and enhanced tangential velocity on their radially outward sides. Principal rainbands are bounded by very dry air on their radially outward sides. Distant rainbands are radially inward-tilting convective features that have dense cold pools near the surface. Inner rainbands are made of shallow convection that appears to have originated from near the eyewall. Differences in the structures of spiral rainbands between observations and the Hurricane Bill simulation are noted. The second part of the study investigates how inner rainbands propagate and makes comparison with previously proposed hypotheses such as vortex Rossby waves.

1. Introduction

Although tropical cyclones (TCs) are often regarded as axisymmetric vortices (e.g., Anthes 1982), asymmetries in TCs play important roles in their evolution. While there exist many different forms of asymmetries in TCs, this study is focused on spiral rainbands, which are banded structures of convection or precipitation in spiral shapes that occur outside the eyewall. Their existence in TCs has been well known for some time, after the first radar images of TCs during World War II showed that precipitation outside the eyewall occurred in coherently banded shapes, rather than being uniformly distributed throughout the storm (e.g., Maynard 1945; Wexler 1947). The importance of spiral rainbands in TCs was recognized early, as the cloud characteristics of TCs—to which spiral rainbands make significant contributions—are often used to help diagnose the current intensity of TCs and forecast their future evolution (Dvorak 1975).

Previous observational studies (e.g., Barnes et al. 1983; Powell 1990a,b; Hence and Houze 2008; Didlake and Houze 2009) suggest that spiral rainbands are transient and small-scale features. To examine such transient and small-scale features, it is necessary to obtain data that are high resolution in both time and space. However, such observations are not readily available yet. For this reason, we turn to numerical simulations. Because of the continuing advances in computational power, it is now feasible to perform cloud-resolving numerical simulations of TCs, and many of the physical processes occurring within real TCs are realistically reproduced [see reviews by Wang and Wu (2004), Wang (2012), and references therein].

A number of previous studies have examined the structures of spiral rainbands in numerical simulations...
of TCs (e.g., Franklin et al. 2005, 2006; Sawada and Iwasaki 2010; Akter and Tsuboki 2012; Li and Wang 2012a,b). However, most of the previous studies used very idealized, no-mean-flow (i.e., no environmental flow) conditions. Akter and Tsuboki (2012) recently examined a real-case simulation of Cyclone Sidr (2007), but their focus was only an outer rainband that formed far \((r \sim 200\,\text{km})\) from the storm center. Other types of spiral rainbands have been noted in previous observational studies, but whether their structures are realistically reproduced in real-case simulations of TCs has not been evaluated in detail. This study helps to fill this gap by carefully examining spiral rainbands in a high-resolution numerical simulation of Hurricane Bill (2009).

Here is how the rest of this paper is organized. First, we discuss the different types of spiral rainbands in section 2 and review previous observational studies of spiral rainbands in section 3. Section 4 describes a numerical simulation of Hurricane Bill (2009), and section 5 discusses identifying notable spiral rainbands during a particular period of the simulation. The structures of principal, secondary, distant, and inner rainbands are described and compared to observations in section 6. Summary and discussions are provided in section 7.

2. Classification of spiral rainbands

When discussing spiral rainbands, it is sometimes necessary to characterize the different convective-scale motions that occur within clouds that make up rainbands. In this study, the terminology proposed by Houze (1997) is followed, which suggested the use of the noun convection to describe “the overturning of the atmosphere that is required to neutralize the vertical distribution of moist static energy” and the adjectives convective and stratiform to describe “the different types of precipitation seen within a given region of convection-generated cumulonimbus.” Convective describes “the precipitation associated with young, active convection,” while stratiform refers to “the precipitation occurring in older, less active convection.” One major difference between convective and stratiform precipitations is that the net vertical transport of precipitating particles is upward in convective regions but close to zero or even slightly negative in stratiform regions.

The term spiral rainbands is somewhat loosely defined, as different types of spiral rainbands exist in a TC. Several different but not mutually exclusive classifications have been proposed. Willoughby et al. (1984) and Willoughby (1988) proposed that there are two types of spiral rainbands: principal and secondary. Principal rainbands extend outward toward one side of a TC and have a strong azimuthal wavenumber-1 signature. They tend to be stationary relative to the storm center and may mark the boundary between the core of a TC and its surrounding environment. Secondary rainbands are usually located in the inner-core region, radially inward of principal rainbands, and they tend to be smaller and more transient. Houze (2010) updated the Willoughby classification by including another type of spiral rainbands: distant rainbands, which are located far from the storm center and contain more vigorous convective elements than principal and secondary rainbands. Figure 1 shows a schematic diagram of this classification.

3. Observed structures of spiral rainbands

Since the first radar images of TCs in the 1940s, subsequent observational studies have documented the structures of spiral rainbands (e.g., Senn and Hiser 1959; Atlas et al. 1963; Barnes et al. 1983; Barnes and Stossmeister 1986; Powell 1990a,b; Barnes et al. 1991; Ryan et al. 1992; Barnes and Powell 1995; Samsury and Zipser 1995). Most of the previous studies were based on observations from single ground-based or airborne Doppler radars, or from composites of pseudo-dual-Doppler radar reflectivity. More recent studies (e.g., Hence and Houze 2008; Didlake and Houze 2009, 2013a,b) used data from the Hurricane Rainband and Intensity Change Experiment (RAINEX; Houze et al. 2006), which collected high-resolution, dual-Doppler radar observations of spiral rainbands in Hurricanes Katrina, Ophelia, and Rita in 2005.

Some commonly observed structures of spiral rainbands from the aforementioned studies are now discussed, following Houze (2010). Careful consideration of the previous literature suggests that a number of previous studies examined principal rainbands (e.g., Senn and Hiser 1959; Powell 1990a,b; Hence and Houze 2008; Didlake and Houze 2009, 2013b), while others documented secondary rainbands (e.g., Barnes et al. 1983; Didlake and Houze 2013a). Although principal and secondary rainbands are different in some aspects (e.g., stationary vs transient), they share many similarities in their structures and they will be discussed together. Figure 2 summarizes the commonly observed structures of principal rainbands in an illustrative schematic diagram, but many features highlighted in Fig. 2 are applicable for secondary rainbands as well.

Principal and secondary rainbands are made up of individual convective cells that tend to form on the upwind sides of the rainbands, travel through them, and dissipate on their downwind sides. For this reason, the upwind regions of principal and secondary rainbands are typically mostly convective while their downwind regions are mostly stratiform (e.g., Atlas et al. 1963; Barnes et al. 1983), although there are large variations from case to
case in the degree of organization (e.g., Ryan et al. 1992; May 1996). The radial location and width of the downwind regions is typically more inward and larger than the upwind regions, respectively (e.g., Senn and Hiser 1959; Hence and Houze 2008). Convective cells within the rainbands tend to move with the layer-averaged flow in which they are embedded, while the rainbands themselves move slower than the layer-mean wind speed; a typical lifetime of these convective cells is shorter than that of rainbands (e.g., Senn and Hiser 1959; Barnes et al. 1991).

A commonly observed kinematic feature of principal and secondary rainband circulations is enhanced tangential velocity on their radially outward sides, which is often maximized above the boundary layer between $z = 2$ and $5 \text{ km}$ (e.g., Powell 1990a,b; Samsury and Zipser 1995; see Figs. 2a,b).

Vertical cross sections through the middle regions of principal and secondary rainbands show that reflectivity cores associated with rainband convection are tilted radially outward with height (e.g., Barnes et al. 1983). When vertical cross sections are taken through updrafts associated with the rainband convection (Fig. 2b), they show an overturning secondary circulation that has radial inflow at lower levels ($z < 2 \text{ km}$) and radial outflow at upper levels around $z = 8 \text{ km}$ (e.g., Barnes et al. 1983). They also show horizontal convergence and divergence at the base and top of rainband convection, respectively (e.g., Hence and Houze 2008). Maximum upward vertical motions are typically found on the radially inward sides of the maximum reflectivity values associated with the rainband convection (e.g., Barnes et al. 1983; Powell 1990a).

When vertical cross sections are taken through downdrafts associated with the rainband convection (Fig. 2c), they show either radial inflow between $z = 2$ and $4 \text{ km}$ that enters the rainbands from their radially outward
sides and descends to the surface while passing through the rainband convection (e.g., Barnes et al. 1983) or an indirectly overturning circulation on their radially inward sides, which has radial outflow that approaches the rainbands around $r = 8$ km, sinking motion on the radially inward side of the rainband convection, and radial inflow at lower levels below $z < 2$ km (e.g., Didlake and Houze 2009). Enhanced tangential velocity is found on the radially inward sides of the rainband convection near $z = 2$ km in association with this indirect overturning circulation.

Recently, Didlake and Houze (2013b) examined the vertical structure of the stratiform, downwind sector of a principal rainband in Hurricane Rita (2005) by taking radius–height cross sections through it. The averaged cross sections (Fig. 2d) show that the rainband convection and its associated reflectivity field are tilted slightly radially outward with height and contain a “bright band” signal near the melting level. It has weak upward and downward motions above and below $z = 4$ km, respectively; the upward motions have radial outward components and thus are tilted radially outward. In addition, there is descending radial inflow toward the rainbands from their radially outward sides. The descending radial inflow and outward-sloped upward motion are associated with enhanced tangential velocity.

Some of the observed kinematic structures of the principal and secondary rainband circulations (e.g., overturning secondary circulation on the radially outward sides of the rainbands) are consistent with the results of a previous idealized study by Moon and Nolan (2010), which argued that these kinematic structures could simply be driven by the response of the tropical cyclone wind field to rainband heating, to the extent that the idealized heating profiles used in Moon and Nolan (2010) are realistic. A few unrealistic aspects of the rainband heating profiles used in Moon and Nolan (2010) are discussed by Didlake and Houze (2013a,b).

Vertical cross sections of equivalent potential temperature ($\theta_e$) through principal and secondary rainbands suggest that lower-$\theta_e$ air ($<340$ K) is often found above $z = 2$ km on the radially outward sides of the rainbands. Rainband updrafts and downdrafts are typically associated with higher and lower $\theta_e$, respectively. In the
averaged view, $\theta_e$ near the surface gradually decreases toward the rainbands from their radially outward sides, reaching relative minimum near the radially inward boundary of the rainbands. This is hypothesized to be due to the downward transport of lower-$\theta_e$ air by downdrafts (e.g., Barnes et al. 1983; Powell 1990b).

In addition to radar observations, other types of observations (e.g., surface observations, dropsondes, and wind profilers) have been used to document rainband structures, especially near the surface, where data coverage by radar is limited because of ground clutter. Some commonly identified features in those studies are that these rainbands are often associated with lower $\theta_e$ near the surface, and that low-level radial inflow toward the storm center is often reduced a bit after passage of rainbands (e.g., Cione et al. 2000; Skwira et al. 2005; Yu and Tsai 2010; Yu and Chen 2011; Eastin et al. 2012; Yu and Tsai 2013).


a. An overview of Hurricane Bill (2009)

Hurricane Bill was a category 4 hurricane that developed from a tropical easterly wave that moved off the west coast of Africa on 12 August. This tropical disturbance organized into a tropical depression by 15 August. Embedded in a deep southeasterly environmental flow with low vertical wind shear and located to the south of a subtropical anticyclone, it developed to a tropical storm by 15 August and to hurricane status by 17 August. Bill continued to strengthen and reached its peak intensity of 115 kt (59 m s$^{-1}$) at 0600 UTC 19 August; Bill maintained its category 4 status for about a day. Starting on 20 August, Bill started to turn northward between the subtropical high and a midtropospheric trough over the East Coast, and its forward speed increased. At the same time, vertical wind shear started to increase, and Bill in response began to weaken gradually. Bill turned northeastward by 23 August and was declared extratropical at 24 August. Avila (2009) and Berg and Avila (2011) provide a more detailed review of Hurricane Bill (2009).

b. Simulation setup

A 3-day period from 1200 UTC 18 August to 1200 UTC 21 August, during which Hurricane Bill was at its peak intensity, is chosen for the simulation. During this period, Hurricane Bill was positioned in the middle of the Atlantic Ocean, so the influence from the land was minimized. The Weather Research and Forecasting (WRF; Skamarock et al. 2008) Model version 3.2.1 is used, with three domains of 9-, 3-, and 1-km horizontal grid spacing for the simulation. The simulation uses the Lambert conformal projection with “true latitudes” of 16.75° and 26.75°N. The 9-km domain centered at 21.75°N, 58.40°W serves as the parent domain of the simulation, which has 384 points in the zonal direction and 336 points in the meridional direction. Figure 3a shows the approximate size of the 9-km domain. The 3- and 1-km domains use 348 × 348 and 624 × 624 points and are nested inside the 9- and 3-km domains, respectively. Both the 3- and 1-km domains are fully two-way interactive and follow the minimum point in the smoothed 850-hPa geopotential height field.

The vertical distribution of the hydrostatic pressure levels ($\eta$) in this WRF simulation of Hurricane Bill is prescribed by using a hyperbolic function of the following form:

$$\eta(x) = \frac{-\tanh(dx/\pi) + \tanh(d/2)}{\tanh(-d/2) + \tanh(d/2)}$$

(1)

where $x = [-\pi/2;\pi/(nz - 1);\pi/2]$ and $nz$ is the total number of vertical levels. The variable $d$ is a parameter that controls the sharpness of the transition zone from 1 to 0, with greater $d$ meaning a sharper transition. All three domains in the simulation have $nz = 61$ and $d = 3.0$. The top of the domain is set at 50 hPa. This $\eta$ distribution results in a stretched grid in height coordinate, with vertical grid spacing of 50 m near the surface gradually transitioning to 500 m near $z = 9$ km. There are 19 levels below $z = 2$ km.

The following parameterizations are used for all domains: the WRF single-moment 6-class microphysics (WSM6; Hong and Lim 2006), Yonsei University planetary boundary layer (YSU; Noh et al. 2003; Hong et al. 2006), and the Goddard shortwave (Chou et al. 1998) and Rapid Radiative Transfer Model longwave (Mlawer et al. 1997) radiation schemes. In the 9-km domain only, the Grell–Dévényi ensemble cumulus scheme (Grell and Dévényi 2002) is used. Convection is explicitly simulated in the 3- and 1-km domains. Surface flux calculation uses the Monin–Obukhov similarity hypothesis with bulk exchange coefficients. The surface drag formulation by Davis et al. (2008) is used, which is tuned to be consistent with Donelan et al. (2004) such that the surface drag coefficient does not continue to increase in high-wind conditions ($>30$ m s$^{-1}$). The enthalpy exchange coefficient follows the formulation by Garratt (1992), where the enthalpy coefficient decreases slightly with increasing wind speed for wind speeds greater than 20 m s$^{-1}$.

Initial and boundary conditions for the simulation are interpolated from the Geophysical Fluid Dynamics Laboratory (GFDL) Hurricane Prediction System. The GFDL initialization is a combination of the Global Forecast System (GFS) initialization and a realistic bogus vortex blended into it to approximately match the size
and intensity of a TC, which are estimated in real time by the National Hurricane Center (see Kurihara et al. 1998; Bender et al. 2007). In addition, a simple, 1D ocean mixed-layer model of Pollard et al. (1972) is used, with the initial mixed-layer depth of 30 m and the vertical temperature gradient of 0.1 K m$^{-1}$ in the thermocline. The lateral boundary conditions for the simulation are interpolated from the GFDL data every 6 h. Time steps of 30, 10, and $3\frac{1}{3}$ s are used in the 9-, 3-, and 1-km domains, respectively. At the beginning of the simulation (1200 UTC 18 August), the center of Hurricane Bill is located near 15.7$^\circ$N, 50.2$^\circ$W, and its azimuthally averaged tangential wind field has the maximum wind speed of 44.6 m s$^{-1}$ and a radius of maximum wind (RMW) of approximately 50 km. Model outputs from the innermost 1-km domain are produced every 2 min between 1800 UTC 19 August and 1800 UTC 20 August.

A baseline metric to measure the performance of real-case simulations of TCs is to compare their track and intensity to the best-track data. Following Nolan et al. (2009), the center of the simulated storm is estimated by the location of minimum surface pressure after the pressure field has been smoothed 500 times with a 1–2–1 filter in both horizontal directions. Figure 3a shows the track of the simulated Hurricane Bill and its best-track data, while Figs. 3b,c show the time evolution of the simulated and best-track minimum sea level pressure and instantaneous maximum surface wind speed. The
simulated track is remarkably close to the best-track data, and the simulated intensity is reasonably reproduced, including the intensity fluctuations during this 3-day period, as the instantaneous wind speeds could be higher than the 1-min averaged wind speeds by up to about 5% (Nolan et al. 2009; Uhlhorn and Nolan 2012).

5. Identifying spiral rainbands at 0800 UTC 20 August

After an initial spinup of the storm, numerous spiral rainbands develop in the Hurricane Bill simulation. First, spiral rainbands at 0800 UTC 20 August are carefully examined, which is 44 h into the simulation (marked by dark green star and lines in Fig. 3). At this time, the simulated storm is well developed. Figure 4 shows azimuthally averaged radial, tangential, and vertical velocity fields composited during a 4-h period centered at this time (between 0600 and 1000 UTC). The simulated Hurricane Bill at this time has a deep cyclonic tangential circulation, with the maximum azimuthally averaged tangential wind speed of 65.4 m s$^{-1}$ near $r = 30$ km. In addition, there exists a well-established secondary circulation of radial inflow below $z = 2$ km toward the storm center, rising motion in the radially outward-tilting eyewall, and radial outflow near $z = 14$ km. A hodograph of environmental horizontal winds, which is defined in this paper as the average in the 3-km domain, shows that the environmental winds transition from southeasterly near the 850-hPa level to southwesterly at the 200-hPa level, indicating the presence of westerly vertical wind shear during this time (not shown).

Figure 5a shows a horizontal cross section at $z = 3.2$ km of reflectivity at 0800 UTC 20 August. Spiral rainbands at this particular time are chosen for detailed examination because their locations and radar depictions appear to resemble those documented in previous observational studies. To help identify the location of spiral rainbands, the vertical velocity field at a lower level (e.g., $z = 2.2$ km, Fig. 5b) is also examined.

In this paper, structures of spiral rainbands are evaluated by taking radius–height cross sections through them as done in previous studies. This procedure can sometimes be difficult because the geometric orientation of spiral rainbands often crosses concentric circles about the center. However, it has been shown that modified logarithmic spirals are good fits to spiral rainbands (e.g., Senn and Hiser 1959). The following form of a modified logarithmic spiral line is used:

$$r = r_{\text{down}}^{*} + (r_{\text{up}} - r_{\text{down}}^{*}) \times \exp\left[-(\lambda - \lambda_{\text{down}}) \tan \alpha\right],$$

(2)
where \( r_{\text{down}}^* = (r_{\text{down}} - A r_{\text{up}})/(1 - A) \), \( A = \exp[-(\lambda - \lambda_{\text{down}}) \tan \alpha] \), \( \alpha \) is a parameter that controls the angle at which the spiral line crosses concentric circles, and \( \Lambda \) is the azimuthal angle between \( \lambda_{\text{up}} \) and \( \lambda_{\text{down}} \). This spiral line is controlled by five parameters: \( r_{\text{up}}, r_{\text{down}}, \lambda_{\text{up}}, \lambda_{\text{down}} \), and \( \alpha \). The \( r \) and \( \Lambda \) parameters \( (r_{\text{up}}, r_{\text{down}}, \lambda_{\text{up}}, \lambda_{\text{down}}) \) are prescribed first, and an appropriate value of \( \alpha \) is manually determined to result in the best fit to each rainband. Figure 6 shows an example of a modified logarithmic spiral line with \( r_{\text{up}} = 300 \text{ km}, \ r_{\text{down}} = 50 \text{ km}, \ \lambda_{\text{up}} = -90^\circ, \ \lambda_{\text{down}} = 180^\circ, \) and \( \alpha = 30^\circ \) in Eq. (2). Red lines show radius–height cross sections along the modified logarithmic spiral line. Dashed concentric circles are for every 50 km.

6. Structures of spiral rainbands at 0800 UTC 20 August

This paper argues that there are four types of spiral rainbands in the Hurricane Bill simulation: principal, secondary, distant, and inner rainbands. Structures of each rainband are first examined and then compared to previous observations discussed in section 3. A difference in the vertical structure of the rainbands, that both principal and secondary rainbands are radially outward-tilted while distant rainbands are radially inward-tilted, will be highlighted.

a. Principal rainband

Figures 7a–e show horizontal cross sections at \( z = 3.2 \text{ km} \) of reflectivity every hour from 0600 to 1000 UTC
20 August. During this period, there is a rainband feature to the east and southeast of the storm center that moves very little over the 4-h period. The averaged reflectivity field from 2-min outputs during the same period also supports the stationary characteristic of this rainband (Fig. 7f). Since this rainband also exhibits a strong azimuthal wavenumber-1-like signature and its location is between \( r = 150 \) and 300 km, it appears to fit the description of a principal rainband (see Fig. 1).
Figures 8a and 8b show horizontal cross sections of reflectivity at $z = 3.2$ km and water vapor mixing ratio at $z = 2.2$ km at 0800 UTC 20 August, while Figs. 8c,d show horizontal cross sections at $z = 0.12$ km of virtual and equivalent potential temperatures ($\theta_v$ and $\theta_e$) at the same time. Figure 8 indicates that the principal rainband is bounded on its radially outward side by very dry air (highlighted by thick solid black lines that spiral radially inward from $r = 300$ to 170 km). Near the surface, it is associated with slightly lower $\theta_v$ and $\theta_e$ (just radially inward of the thick solid black lines in Fig. 8). Note that much stronger surface $\theta_v$ and $\theta_e$ depressions are located on the other side of the storm, which are associated with the distant rainband (see section 6c). A close-up view of this principal rainband is shown in Figs. 9a,b. Also shown on Figs. 9a,b are thick solid black lines from Fig. 8 to highlight the radially outward boundary of the principal rainband. Figures 9a,b suggest that this principal rainband is made up of scattered convective cells, instead of a single well-organized continuous line of convective updrafts.

To examine the vertical structure of the principal rainband, 77 radius–height cross sections are taken at black asterisks in Figs. 9a,b, where reflectivity value and vertical velocity at $z = 3.2$ km are greater than 20 dBZ and $4 \text{ m s}^{-1}$ in the middle region of the principal rainband, respectively. Figures 9c–h show averaged radius–height cross sections of reflectivity; vertical, radial, and tangential velocities; $\theta_v$; and asymmetric tangential velocity, respectively. The averaged radius–height cross sections in Figs. 9c,d indicate that the vertical structure of the principal rainband is tilted radially outward. Upward vertical velocity is very closely collocated with the reflectivity cores, with the maximum upward motions located slightly radially inward of the maximum reflectivity values. In addition, there is radial inflow...
toward the rainband on its radially outward side at lower levels below $z = 3$ km and radial outflow near $z = 8$ km (Fig. 9e), indicating that there is an overturning secondary circulation on the radially outward side of the principal rainband. Tangential velocity is enhanced on the radially outward side of the rainband near $z = 4$ km (Fig. 9f). This enhancement is more visible on the averaged radius–height cross section of asymmetric tangential
velocity in Fig. 9h. These kinematic structures are consistent with previous observational studies [e.g., Powell (1990a); Hence and Houze (2008); see section 3]. $\theta_e$ is greater (>355 K) near the surface, and its minimum (<340 K) is centered near $z = 4 \text{ km}$ (Fig. 9g). Slightly greater $\theta_e$ is found along the radially outward-sloped rainband updrafts. These $\theta_e$ structures are in agreement with previous observational studies, except that the $\theta_e$ minimum is located a bit higher up [e.g., Powell (1990b); see section 3]. Radius–height cross sections taken through other rainband updrafts and their averages show similar structures (not shown).

Previous observations have indicated that radius–height cross sections taken through downdrafts embedded within principal rainbands show radial inflow between $z = 2$ and 4 km that descends to the surface while approaching the rainbands from their radially outward sides [e.g., Hence and Houze (2008); see Fig. 2c and section 3]. An example of this structure is shown in the left column of Fig. 10. A radius–height cross section is taken along the black solid line (marked by arrow) in Fig. 10a, and Figs. 10b–d show radius–height cross sections of reflectivity, tangential velocity, and $\theta_e$. Vectors on Figs. 10b–d show radial and vertical velocity fields at the same time along the black line. Figures 10b–d show that radial inflow on the radially outward side of the rainband between $z = 2$ and 4 km turns downward while approaching the rainband. This descending motion is associated with lower $\theta_e$, although the location of maximum downward motion is not exactly collocated with lowest $\theta_e$ value in the neighborhood in this snapshot (Fig. 10d). Many radius–height cross sections through relatively strong downdrafts ($w < -3 \text{ m s}^{-1}$) embedded within the principal rainband around 0800 UTC 20 August typically show this descending midlevel radial inflow (not shown).

Another kinematic structure highlighted in radius–height cross sections through downdrafts embedded in principal rainbands is the indirect overturning circulation on the radially inward sides of the rainbands, which is made of radial outflow that approaches the rainbands from their radially inward sides around $z = 8 \text{ km}$, sinking motion on the radially inward sides of the rainband convection, and radial inflow at lower levels below $z < 2 \text{ km}$ [e.g., Hence and Houze (2008); Didlake and Houze (2009); see Fig. 2c and section 3]. Enhanced tangential velocity is found on the radially inward sides of the rainband convection near $z = 2 \text{ km}$ in association with this indirect overturning circulation. An example that best resembles this structure is shown in the right column of Fig. 10. A radius–height cross section is taken along the black solid line (marked by arrow) in Fig. 10e. Figures 10f–h are similar to Figs. 10b–d, except that they are taken along the black line in Fig. 10e. Figures 10f–h show radial outflow aloft near $z = 7 \text{ km}$, sinking motion on the radially inward side of the rainband convection, and radial inflow below $z = 2 \text{ km}$ that resembles the indirect overturning circulation in previous observations. The sinking motion is associated with slightly lower $\theta_e$ (Fig. 10h). However, enhanced tangential velocity at lower levels (e.g., $z < 2 \text{ km}$) is not found near this indirect overturning circulation. Many radius–height cross sections have been taken through relatively strong downdrafts embedded within the principal rainband between 0730 and 0830 UTC 20 August, but none has captured the enhanced low-level tangential velocity associated with the indirect overturning circulation (not shown). In addition, indirect overturning circulations appear to occur less frequently than descending midlevel radial inflows on the radially outward side during this period (not shown).

Figure 11 shows partitions of convection into convective and stratiform components at 0800 UTC 20 August. Two different but complementary methods are considered. The first is adopted from Rogers (2010), which is based on the algorithm of Steiner et al. (1995). This method examines a horizontal distribution of reflectivity at $z = 3.2 \text{ km}$ (hereafter, “reflectivity based”). The second method is adopted from Braun et al. (2010), which is similar to Tao et al. (1993). This method examines mainly a distribution of surface rainfall rate (hereafter, “rainfall based”). Both partitions agree that the upwind region of the principal rainband is mostly convective, and there is considerable stratiform convection in its downwind region (i.e., to the north of the storm center), consistent with previous results [e.g., Atlas et al. (1963), Barnes et al. (1983); see section 3].

Now, radius–height cross sections are taken through the stratiform region of the principal rainband. Following Didlake and Houze (2013b), 90 radius–height cross sections are taken at points between $r = 145$ and 190 km to the northeast from the storm center, where horizontal divergence at $z = 3.8 \text{ km}$ is less than $-2 \times 10^{-3} \text{ s}^{-1}$ (see black stars in Fig. 12a). Figures 12b–g show averaged radius–height cross sections of reflectivity, vertical, radial, tangential velocities; $\theta_e$; and asymmetric tangential velocity. Figure 12b shows that reflectivity structures associated with the principal rainband are tilted radially outward with height, with a bright band feature present near $z = 5 \text{ km}$, especially on the radially outward side of the rainband. There are rising motions above $z = 4 \text{ km}$ but sinking motions below $z = 4 \text{ km}$ (Fig. 12c), which is the typical vertical velocity profile expected in the stratiform region of convective clouds (e.g., Houze 1997). This vertical dipole of vertical velocity shows a slight radially outward tilt. Figure 12d shows that the
FIG. 10. (a) A horizontal cross section at $z = 2.2\text{ km}$ of vertical velocity at 0800 UTC 20 Aug about the middle region of the principal rainband. (b)–(d) Radius–height cross sections of reflectivity, tangential velocity, and equivalent potential temperature along the black line in (a), with overlaid vectors showing radial and vertical velocity fields at the same time along the black line. Dark green lines in (b)–(d) show $-3$, $-2$, and $-1\text{ m s}^{-1}$ of vertical velocity. (e)–(h) As in (a)–(d), respectively, but at 0738 UTC 20 Aug. Dark green lines in (f)–(h) show $-2$ and $-1\text{ m s}^{-1}$ of vertical velocity. Dashed concentric circles in (a),(e) are for every 50 km.
rising motions of the vertical dipole structure are associated with radial outflow (near $z = 5\ km$). In addition, Fig. 12d shows that there is radial inflow on the radially outward side of the rainband that appears to descend toward the rainband (near $z = 2\ km$). However, this radial inflow is located near $z = 3\ km$, which is lower than $z > 5\ km$, as documented in Didlake and Houze (2013b). Taking radius–height cross sections further radially outward (see magenta stars in Fig. 12a) shows this descending midlevel radial inflow at a higher altitude near $z = 4\ km$ (Fig. 12h) but still lower than that in Didlake and Houze (2013b). Another kinematic feature highlighted in Fig. 2d is radial outflow near $z = 2\ km$ just above the low-level radial inflow on the radially outward side of the rainband. Figure 12d (and individual cross sections that make up Fig. 12d) does not show radial outflow near $z = 2\ km$ just above the low-level radial inflow, but the magnitude of the radial inflow at this height is considerably weaker. Tangential velocity is enhanced on the radially outward side of the rainband near $z = 4\ km$ (see Figs. 12e,g). Figure 12f shows that this stratiform region of the principal rainband is bounded by very-low-$\theta_e$ air on the radially outward side of the rainband, and this low $\theta_e$ is collocated with the descending radial inflow shown in Fig. 12d. The structures of the stratiform region of the principal rainband are mostly in agreement with Didlake and Houze (2013b), except that the descending midlevel radial inflow on the radially outward side is at a lower altitude and the low-level radial outflow is weaker or absent.

b. Secondary rainband

Figure 5 shows another spiral rainband of interest to the south and east of the storm center between $r = 75$ and 150 km. It is located between the eyewall and the principal rainband, and this rainband is transient, moving with time (Fig. 7), fitting the description of a secondary rainband (see Fig. 1). A close-up view of this secondary rainband is shown in Fig. 13. Also shown on Fig. 13a is a thick dashed black line that spirals radially inward from $r = 110$ to 74 km to help identify the approximate location of this secondary rainband.

Examining a horizontal cross section of vertical velocity at $z = 2.2\ km$ (Fig. 13b) indicates that this secondary rainband is associated with a fairly continuous line of updrafts with a few breaks. The rainband is divided into four different regions, and four separate modified logarithmic lines are fitted through the rainband updrafts (solid black lines in Fig. 13b). Radius–height cross sections are taken in S1 to S4 and averaged in each region. To highlight how the structure varies along this rainband, only averages of 61 and 73 cross sections in S1 and S4 are shown, respectively.

Figure 14 shows averaged radius–height cross sections of reflectivity; vertical, radial, tangential, and asymmetric tangential velocity fields; and $\theta_e$ in S1 and S4. Figures 14a,g show that reflectivity cores associated with
this secondary rainband are tilted radially outward with height in both S1 and S4. Updrafts are closely collocated with those reflectivity cores and also tilted radially outward with height (Figs. 14b,h). In S1, the strongest upward motions are located radially inward of the largest reflectivity values (Fig. 14a). Unlike in S1, a bright band appears near $z = 5 \, \text{km}$ in S4 (Fig. 14g), indicating that convection in this region is fully developed and has begun to decay, which supports the characterization that this secondary rainband becomes more stratiform in the downwind direction (e.g., Barnes et al. 1983). Reflectivity values in the middle and upper troposphere ($z > 8 \, \text{km}$)
are higher in S4, likely because of the closer proximity to the eyewall, so that there are more frozen condensates exhausted from the eyewall into the upper-level outflow region. In both S1 and S4, there are low-level \((z < 2 \text{ km})\) radial inflow toward the rainband and radial outflow away from the rainband aloft \((z > 6 \text{ km})\) on its radially outward side (Figs. 14c,i), which in conjunction with the averaged radius–height cross sections of vertical velocity (Figs. 14b,h) indicate there is an overturning circulation on the radially outward side of the rainband in both regions. There is horizontal convergence near \(r = 0 \text{ km}\) below \(z = 2 \text{ km}\) at the base of the rainband updraft; the magnitude of this horizontal convergence is greater in S1, as the decrease of low-level radial inflow near the rainband updraft is greater in S1 (see Figs. 14c,i). The low-level radial inflow is deeper in S1 than in S4. On the radially outward side of the rainband, tangential velocity between \(z = 2 \text{ and } 6 \text{ km}\) is slightly enhanced in S4 (Figs. 14j,k), but this is not evident in S1 (Figs. 14d,e). Examining radius–height cross sections of tangential velocity in S2 and S3 indicates that this enhancement of tangential velocity on the radially outward side becomes gradually more apparent from S1 to S4 (not shown). Figures 14f,l show that lower \(\theta_e\) values are found near \(z = 4 \text{ km}\), and the rainband convection is associated with higher \(\theta_e\) than its surroundings. Another region of \(\theta_e\) minimum is found near \(z = 8 \text{ km}\) in S1. Overall, these kinematic and \(\theta_e\) structures are mostly in agreement with previous observations [e.g., Barnes et al. (1983); Powell (1990a,b); Hence and Houze (2008); see section 3].

As in principal rainbands, previous observational studies noted that vertical cross sections through downdrafts associated with secondary rainbands show either a descending midlevel radial inflow on their radially outward sides or an indirect overturning circulation on their radially inward sides (see Fig. 2c and section 3). Examining individual cross sections through the secondary rainband at 0800 UTC 20 August (Figs. 13 and 14) does not clearly show these features. However, a radius–height cross section through the secondary rainband at an earlier time (0752 UTC 20 August) shows the existence of the descending midlevel radial inflow near \(z = 2 \text{ km}\) on the radially outward side (Figs. 15a–d). At 0730 UTC 20 August, there is a hint of the previously highlighted indirect overturning circulation on the radially inward side of the secondary rainband (Figs. 15e–h). Tangential velocity is slightly enhanced on the radially inward side near \(z = 2 \text{ km}\). As in the principal rainband case, many radius–height cross sections through strong downdrafts embedded within the secondary rainband show the descending midlevel radial inflows on the radially outward side. However, it is considerably more difficult to find radius–height cross sections through the secondary rainband downdrafts that show the indirect overturning circulations around 0800 UTC 20 August (not shown).
FIG. 14. Averaged radius–height cross sections of (top)–(bottom) reflectivity, vertical velocity, radial velocity, tangential velocity, asymmetric tangential velocity, and equivalent potential temperature in (a)–(f) S1 and (g)–(l) S4 of the secondary rainband shown in Fig. 13. Black lines show vertical velocity of 1 and 3 m s\(^{-1}\) in (a)–(f) and of 2 m s\(^{-1}\) in (g)–(l).
Fig. 15. (a) A horizontal cross section at $z = 2.2$ km of vertical velocity at 0752 UTC 20 Aug about the secondary rainband. (b)–(d) Radius–height cross sections of reflectivity, tangential velocity, and equivalent potential temperature along the black line in (a), with overlaid vectors showing radial and vertical velocity fields at the same time along the black line. Dark green lines in (b)–(d) show vertical velocities of $-2$ and $-1$ m s$^{-1}$. (e)–(h) As in (a)–(d), respectively, but at 0730 UTC 20 Aug. Dark green lines in (f)–(h) show vertical velocities of $-1.5$ and $-1$ m s$^{-1}$. Dashed concentric circles in (a) and (e) are for every 50 km.
Figures 5 and 13 suggest that this secondary rainband appears to extend further downwind toward \( r = 60 \) km to the north of the storm center. One particular feature regarding the downwind region of the secondary rainband noted in previous studies was that convection embedded in this region was decaying and more stratiform than in its upwind region [e.g., Barnes et al. (1983); see section 3]. The reflectivity-based and rainfall-based convective-stratiform partitions in Fig. 11 show qualitatively similar results that the secondary rainband is mostly convective in its upwind region. The downwind region of the secondary rainband is mostly stratiform, as the area of stratiform convection increases in the downwind direction. Radius–height cross sections have been taken in S5 of the secondary rainband (Fig. 13), where convection is predominantly stratiform. Their averages look similar to those in S4, except that the bright band feature appears more evident, supporting the stratiform characteristics of the rainband convection in S5 (not shown). In addition, radius–height cross sections have been taken at points near S5 between \( r = 60 \) and 90 km, where horizontal divergence at \( z = 3.8 \) km is less than \(-3 \times 10^{-3} \) s\(^{-1}\). Their averages look similar to those presented in Fig. 12. A few notable differences are that there is no descending mid-level radial inflow on the radially outward side; the enhanced tangential velocity on the radially outward side is maximized lower near \( z = 2 \) km; and the value of minimum \( \theta_e \) (~345 K) is greater than that in Fig. 12f (~325 K) and is located higher, near \( z = 3.5 \) km (not shown).

Figure 8d shows that the secondary rainband (thick dashed black line) is associated with relatively high \( \theta_e \) values (>350 K) near the surface. In S1 (the upwind region of the dashed line), surface \( \theta_e \) values are higher on its radially outward side than on its radially inward side. Figure 8d also shows that pockets of slightly lesser \( \theta_e \) are present on its radially outward side. Comparison with vertical velocity fields (e.g., Figs. 5b and 13b) indicates that these low \( \theta_e \) values are often closely collocated with sinking motions, suggesting that low-\( \theta_e \) air might have been transported downward from above near \( z = 4 \) km, as hypothesized previously (e.g., Barnes et al. 1983). Figure 8c shows that the upwind region of the secondary rainband is associated with slightly lower \( \theta_e \) near the surface, but the magnitude of its depression is rather weak (<2 K). The horizontal gradient of \( \theta_e \) associated with the secondary rainband near the surface is smaller than indicated in previous observations (see section 3).

Close examination of horizontal cross sections of reflectivity (e.g., Figs. 5 and 7) between 0700 and 0900 UTC of 20 August indicates that this secondary rainband moves slightly radially outward and also into the downwind direction. However, tracking individual convective cells that make up this rainband finds that these individual convective cells tend to form on its upwind region, travel through the rainband, and dissipate in its downwind region (not shown).

c. Distant rainband

Figure 5 shows a rainband located to the west of the storm center near \( r = 225 \) km. Since this rainband is located far away from the center on the opposite side of the principal rainband and is made up of convectively active elements, it fits the description of a distant rainband (see Fig. 1). A close-up view of this distant rainband is shown in Fig. 16. Figure 17 shows horizontal cross sections at \( z = 22 \) m of air density, \( \theta_e \), water vapor mixing ratio, and \( \theta_c \). This distant rainband, which is
located near \( x = -200 \text{ km}, y = 30 \text{ km}, \) and \( r = 225 \text{ km} \), is clearly associated with locally dense air near the surface, indicating that it is associated with surface cold pools. In addition, this rainband is collocated with lower \( \theta_e \), lower water vapor mixing ratio (thus, lower \( u_y \)), and lower \( u_e \).

To examine the vertical structure of this distant rainband, 36 radius–height cross sections are taken along the black line in Fig. 16 (see black arrows). Figure 18 shows averaged radius–height cross sections of reflectivity; vertical, radial, and tangential velocities; horizontal divergence; and \( \theta_e \). The most prominent feature of this distant rainband is that it tilts radially inward with height (Fig. 18a), which is opposite from the principal and secondary rainbands examined in sections 6a and 6b.

The rainband updraft is located on the radially outward edge of the rainband and also tilts inward (Fig. 18b). Strongest upward motions are located on the radially outward side of maximum reflectivity values. Weak sinking motions are present below the rainband updrafts. The rainband convection is associated with low \( \theta_e \) and radially outward motion near the surface (Figs. 18c,f). The depth of the surface cold pool is about 1 km. At the base of the rainband convection (near \( r = 0 \text{ km} \) and \( z = 1 \text{ km} \)), there is strong horizontal convergence associated with radial inflow and outflow from its radially outward and inward sides, respectively (Fig. 18e). This radial inflow is very shallow (\( z < 1 \text{ km} \)) and is associated with high-\( \theta_e \) air. The low-level radial inflow is lifted near the base of the rainband axis and becomes collocated with the rainband updraft throughout the depth of the rainband, indicating that mechanical lifting is occurring along the leading edge of the distant rainband. The rainband updraft has higher \( \theta_e \) than its surroundings. Horizontal convergence and divergence are located below and above the rainband updraft, respectively, and the rainband updraft axis closely follows the line of zero horizontal divergence. There is a pocket of stronger horizontal divergence near \( z = 3 \text{ km} \) and there is a radial
outflow to the radially outward side from it. Detrainment of high $\theta_e$ from the rainband updraft along this radial outflow is obvious at this altitude. The $\theta_e$ minima are found near $z = 1.5$ and 8 km. Tangential velocity is enhanced along the rainband updraft (Fig. 18d), which is collocated with radial inflow, suggesting that tangential velocity is enhanced as a result of angular momentum conservation. The surface cold pool is associated with weaker tangential velocity in comparison to the radially outward side of the rainband, again because of its radial outward motion and associated angular momentum conservation. Vertical cross sections through different parts of this distant rainband in Fig. 16 reveal very similar structures (not shown).

Figure 19 shows horizontal cross sections at $z = 0.12$ km of $\theta_e$ every 30 min between 0700 and 1100 UTC 20 August, with overlaid red lines showing $-4 \times 10^{-3}$ s$^{-1}$ of horizontal divergence at the same height and time. They show that the distant rainband shown in Fig. 16 forms around 0700 UTC near $r = 200$ km to the northwest of the storm center and moves around the center, while moving radially outward over time. By 1100 UTC, the rainband is near $r = 300$ km to the southwest of the storm center. Strong horizontal convergence is always present at the leading edge of the distant rainband during this period. The magnitude of the surface cold pool decreases after 0900 UTC, and its radially outward motion slows down.

Our finding that distant rainbands are tilted radially inward with height and have surface cold pools with lifting occurring at their leading edges is consistent with Yu and Tsai (2013). It appears that the rainband documented in Barnes et al. (1991) might have been a distant rainband as well. The structure of distant rainbands shares many similarities with squall lines [cf. Fig. 18 in this paper with Fig. 14 from Houze (2004)].
Although not discussed by Houze (2010), previous studies have identified so-called inner rainbands, which form just outside the eyewall and propagate radially outward with time while being advected around the storm center (e.g., Wang 2008, 2009). These inner rainbands are believed to be the manifestation of vortex Rossby waves [e.g., Montgomery and Kallenbach (1997); Corbosiero et al. (2006); see Moon and Nolan (2015, hereafter Part II) for more details].

Figure 5 shows an inner rainband feature just outside the eyewall to the south and southeast of the storm center near $r = 50$ km. A close-up view of this inner rainband is shown in Figs. 20a,b when the rainband is located near $x = 30$ km, $y = -45$ km, and $r = 50$ km (see black arrow).
secondary rainband (see Fig. 13) lies to the east of this inner rainband. Figures 20c,d show horizontal cross sections at \( z = 0.12 \) km of \( u_y \) and \( \theta_e \) about the inner rainband, respectively, with magenta lines highlighting 30-dBZ reflectivity. They show that the inner rainband is associated with strong rising motions on its radially outward side but sinking motions on its radially inward side. It is difficult to identify \( u_y \) or \( \theta_e \) anomalies near the surface associated with the rainband.

A total of 30 radius–height cross sections are taken along the rainband in Fig. 20. Figure 21 shows averages of reflectivity; vertical, radial, and tangential velocities; \( \theta_e \); and rainwater, cloud water, graupel, snow, and cloud ice mixing ratios. They indicate that this inner rainband is shallow, as the reflectivity core associated with it extends only up to \( z = 5 \) km. There are some moderate reflectivity values above \( z = 7 \) km, but they are due to the frozen condensates from the eyewall convection that are exhausted into the upper-level outflow and sink gradually downward. While there are rising and sinking motions on its radially outward and inward sides, respectively, this horizontal dipole of vertical velocity is shallow, existing only between \( z = 1.5 \) and \( 3.5 \) km. It is unclear whether this rainband is vertically tilted, as its reflectivity core tilts slightly radially outward with height, but its vertical velocity structure tilts slightly radially inward with height. Its \( \theta_e \) minimum is found around \( z = 3 \) km on both the radially inward and outward sides of the rainband. There is a strip of high cloud water mixing ratio, lower tangential velocity, and reduced radial inflow near \( z = 1 \) km on the radially inward side of the rainband. Since these anomalous features are associated with higher \( \theta_e \), it appears possible that this rainband may have originated from near the eyewall and moved radially outward with time. How these inner rainbands propagate will be investigated in the second part of this study (Part II). To the best of our knowledge, the structures of inner rainbands have not been documented in observations, so it is difficult to say whether...
the structures of inner rainbands in this Hurricane Bill simulation are realistic or not.

7. Summary

This is the first part of a comprehensive study that examines spiral rainbands in a numerical simulation of Hurricane Bill (2009). Four types of spiral rainbands have been identified: principal, secondary, distant, and inner rainbands. Although principal rainbands tend to be stationary relative to the storm center and secondary rainbands are transient and move around the storm center, both rainbands are tilted radially outward with height and have many kinematic features identified in FIG. 21. Radius–height cross sections averaged along the black line in the inner rainband shown in Fig. 20 of (a) reflectivity; (b) vertical, (c) radial, and (d) tangential velocities; (e) equivalent potential temperature; and (f) rainwater, (g) cloud water, (h) graupel, (i) snow, and (j) cloud ice mixing ratios. Thick solid black lines show 20- and 30-dBZ reflectivity.
previous observational studies, such as overturning secondary circulation, descending midlevel radial inflow, and enhanced tangential velocity on the radially outward sides of the rainbands. In addition, principal rainbands are bounded by very dry air on their radially outward sides. These structures of principal and secondary rainbands are in agreement with previous observational studies (see section 3). However, examining radius–height cross sections through principal and secondary rainbands suggests that indirect overturning circulations on the radially inward sides of the rainbands are not well represented in this 1-km simulation of Hurricane Bill around 0800 UTC 20 August. Distant rainbands are tilted radially inward with height and are associated with locally dense surface cold pools; they move radially outward with time, while being advected around the storm center in a cyclonic direction. Inner rainbands are shallow convective features that appear to have originated from near the eyewall region. Part II will evaluate how inner rainbands in the Hurricane Bill simulation propagate and make comparisons with previously proposed hypotheses, such as vortex Rossby waves.

This paper has evaluated the structures of spiral rainbands from a single real-case simulation at around a particular time period, under certain vertical wind shear and environmental conditions. It would be of interest to examine how differently the position and structures of spiral rainbands evolve over time. A glance of rainbands between 0600 and 1000 UTC 20 August suggests that principal and secondary rainbands are present during this period, with their intensity fluctuating over time, although it is difficult at times to discern one from the other. Distant rainbands are more transient than principal and secondary rainbands and are often located on the opposite side of principal rainbands. Inner rainbands are almost always present just outside the eyewall during this period. One difference that was not fully explored in section 6 is that the near-surface horizontal gradients of \( \theta_e \) associated with principal and secondary rainbands are not as strong as those noted in previous studies. A future study will explore how the differences in the environmental conditions, such as vertical wind shear, affect the structures and evolution of spiral rainbands.

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