ABSTRACT

Based on a successful cloud-resolving simulation with the Weather Research and Forecasting Model, this study examines key processes that led to the early development of Hurricane Dolly (2008). The initial development of Dolly consisted of three stages: (i) an initial burst of convection; (ii) stratiform development, dry intrusion, and thermodynamic recovery; and (iii) reinvigoration of moist convection and rapid intensification. Advanced diagnosis of the simulation—including the use of vorticity budget analysis, contour frequency analysis diagrams, and two-dimensional spectral decomposition and filtering—suggests that the genesis of Dolly is essentially a “bottom-up” process. The enhancement of the low-level vorticity is mainly ascribed to the stretching effect, which converges the ambient vorticity through stretching enhanced by moist convection. In the rapid intensification stage, smaller-scale positive vorticity anomalies resulting from moist convection are wrapped into the storm center area under the influence of background convergent flow. The convergence and accompanying aggregation of vorticity anomalies project the vorticity into larger scales and finally lead to the spinup of the system-scale vortex. On the other hand, although there is apparent stratiform development in the inner-core areas of incipient storm after the initial burst of convection, little evidence is found to support the genesis of Dolly through downward extension of the midlevel vorticity, a key process in the “top-down” thinking.

1. Introduction

Tropical cyclone (TC) formation is a complex problem in dynamical and tropical meteorology because it involves interactions among physical processes that vary over multiple space and time scales. The large-scale climatological conditions favorable for the formation of TCs have been well known since Gray (1968) and were summarized later by Briegel and Frank (1997) and others: sea surface temperature of at least 26.5°C coupled with a relatively deep thermocline, organized deep convection with high midlevel humidity, weak and preferably easterly vertical wind shear, and cyclonic midlevel relative vorticity. More recently, the role of tropical wave activity in the organization of deep convection as a precursor to TC formation has received increased attention. Frank and Roundy (2006) proposed that the favorable anomalies producing most of the world’s tropical cyclones are organized by one or more tropical waves, often as they interact with a monsoon trough and/or each other. Webster et al. (2005) hypothesized that the equatorial variability of the basic state (vertical and horizontal shear and longitudinal stretching deformation) alters the characteristics of equatorial waves to form regions of energy accumulation, which are critical to the development of TCs in nonmonsoonal regions. Dunkerton et al. (2008) further pointed out that the critical layer of tropical waves could be a “pouch” or “sweet spot” for TC formation.

There are many unresolved and debatable issues surrounding mesoscale dynamical processes relating to TC formation. One such issue concerns the way in which mesoscale deep convection is organized to form a larger-scale TC vortex. The earliest investigators suggested that the cooperative interaction between deep convection and the surface large-scale circulation is a positive feedback process by which an incipient tropical disturbance can be intensified and ultimately developed into
a TC (Charney and Eliassen 1964; Ooyama 1964). This was coined the conditional instability of the second kind (CISK). Since the late 1980s, the CISK mechanism has been challenged by the wind-induced surface heat exchange (WISHE) instability, a principal theory proposed as an alternative to CISK by Emanuel (1986) and Rotunno and Emanuel (1987). In the framework of WISHE, winds associated with a surface vortex enhance fluxes of sensible and latent heat from the ocean surface, and vigorous convection transports the energy from the ocean surface to the upper troposphere and then fuels the intensification of the vortex. Since both the CISK and WISHE theories require a preexisting surface-concentrated vortex of sufficient amplitude (tropical depression) to spin up TCs, the natural issue of TC formation has turned to how such a “sufficient” disturbance forms in the first place.

More recently, two competing theories (namely, “top down” and “bottom up”) have been proposed to explain the formation of a surface vortex with sufficient amplitude. In top-down thinking, the surface circulation results from the downward extension of a midlevel vortex, which presumably forms within the stratiform precipitation region of a mesoscale convective system (MCS). In bottom-up thinking, the convergence and stretching associated with deep convection engenders a surface circulation. Recent studies based on the analysis of a variety of research aircraft and conventional observational datasets suggest that the mesoscale convective vortices (MCVs) that form in the stratiform precipitation areas of tropical MCSs can be a precursor to tropical cyclogenesis (Harr et al. 1996; Simpson et al. 1997; Ritchie and Holland 1997; Bister and Emanuel 1997). Simpson et al. (1997) and Ritchie and Holland (1997) observed that these MCVs sometimes merge to result in a more intense vortex with increased horizontal and vertical scales. This process can increase low-level vorticity and intensify a tropical disturbance and is a primary physical mechanism in top-down thinking. Instead of emphasizing the importance of the merger process, Bister and Emanuel (1997) argued that sustained precipitation in the stratiform cloud deck would gradually saturate the relatively dry and cold layer below from the top down. In addition, they hypothesized that a mesoscale downdraft within stratiform precipitation could advect midlevel cyclonic vorticity to the surface to facilitate the development of the surface vortex.

In contrast to the top-down thinking, the bottom-up scenario sees surface-based convection as the key to generating the TC vortex. Montgomery and Enagonio (1998) and Möller and Montgomery (2000) demonstrated that low-level vortex merger and axisymmetrization of small-scale positive potential vorticity (PV) anomalies resulting from the hot-tower-like “convective bursts” (coined vortical hot towers, or VHTs) could intensify a larger-scale vortex on realistic time scales. In addition to emphasizing the importance of the VHT interactions, Hendricks et al. (2004) and Montgomery et al. (2006) further pointed out that the primary forcing for the mean vortex development was the system-scale deep convection, which drives a toroidal circulation and then organizes the angular momentum into the vortex. Despite the lower resolution of their numerical model, Tory et al. (2006a,b) also found that the formation and merger of VHT-like anomalies led to the formation of the dominant vortex that became the TC core in simulations of tropical cyclogenesis in the Australian region. The observational evidence of VHTs during tropical cyclogenesis provided by Reasor et al. (2005) and Sippel et al. (2006) indicates that the bottom-up process might be a real pathway to the formation of a surface vortex with sufficient amplitude to commence WISHE.

Based on observational analysis of a number of developing TCs, Raymond et al. (1998) suggested that processes associated with both top-down and bottom-up thinking could take place sequentially in the early development of a TC. During the early stages of development, the MCS kinematic structure resembled that of a system dominated by stratiform dynamics and then became increasingly more convective as the system intensified. They also found that the transition appeared to be coupled with an increase in the midlevel relative humidity. Such a moistening process also occurred before the formation of the incipient surface vortex of TCs in Bister and Emanuel (1997) and Nolan (2007).

This study examines the initial development of Hurricane Dolly (2008), focusing on the evolution of the low-level vortex and the related dynamics and thermodynamics with the intention of identifying in what manner a preexisting easterly wave finally developed into a hurricane. The synoptic background behind this case will be introduced in section 2. Section 3 describes the experiment and methodology. A three-stage initial development of Dolly is presented in section 4. Section 5 examines the relevance of the bottom-up versus top-down hypotheses in Dolly’s initial development. Concluding remarks are given in section 6.

2. Synoptic background

Hurricane Dolly was the fourth tropical cyclone and second hurricane that formed during the 2008 Atlantic hurricane season. It made landfall at the Texas–Mexico border and was the first U.S. landfalling hurricane of the 2008 season. Dolly caused widespread power outages and extensive tree damage in Texas. A rough estimate of
the total U.S. damage due to Dolly was around $1.05 billion (Pasch and Kimberlain 2009).

The origin of Dolly was closely linked with a tropical wave. Early on 11 July, an easterly wave crossed the west coast of Africa and entered into the Atlantic Basin. Over the next several days, the wave moved generally westward and intensified gradually. At around 1200 UTC 16 July, the well-organized wave reached the eastern Windward Islands. The following evolution of this tropical disturbance is similar to the precursors of TCs discussed by Dunkerton et al. (2008). Figure 1 shows the 850-hPa relative vorticity and horizontal streamlines in a reference frame translating westward at the zonal propagation speed of the easterly wave (−7.4 m s\(^{-1}\)) as estimated from the Hovmöller method (Dunkerton et al. 2008) from 1200 UTC 16 July at 24-h intervals. From the panels in Fig. 1, it is obvious that as the wave propagated westward, the distinct vorticity disturbance was always situated in the critical layer, where the mean flow and wave phase speeds are equal. Although the critical layer is a pouch or sweet spot for TC formation, as suggested by Dunkerton et al. (2008), with a moist lower-to-middle troposphere and sea surface temperature well above 26.5°C, sustainable development of this tropical disturbance did not take place for several days (Figs. 2a,b); the TC genesis timing remains difficult to determine (Dunkerton et al. 2008). This was possibly because of the increase of the vertical wind shear (\(V_{200\text{hPa}} - V_{850\text{hPa}}\)) to more than 10 m s\(^{-1}\) as the disturbance moved westward after 1200 UTC 17 July (Fig. 2b).

Beginning around 1200 UTC 18 July, the vorticity disturbance located in the pouch began to depart from its original westward propagation and took a northwest track (Figs. 1c–e). After the precursor of Dolly entered the Caribbean Sea, the environmental conditions became more favorable for TC development with an even warmer sea surface, a moister lower-to-middle troposphere, and a reduction in large-scale vertical wind shear (Fig. 2). At 1200 UTC 20 July, the shear was approximately 6.5 m s\(^{-1}\), which would be categorized as a “weak shear” (less than or near 10 m s\(^{-1}\)) and that which is necessary to help force synoptic-scale ascent during tropical cyclogenesis (Bracken and Bosart 2000). In the meantime, there was a gradual deepening of the moisture for the entire time period shown and a marked increase in low-level moisture beginning around 0000 UTC 19 July.

At around 1200 UTC 20 July, a well-defined low-level circulation center was centered about 500 km east of Chetumal, Mexico (Pasch and Kimberlain 2009). However, the system soon became disorganized and the circulation center temporarily became difficult to track. After 1200 UTC 21 July, when the system was to the north of the Yucatan Peninsula, it reorganized and finally strengthened into a hurricane by 0000 UTC 23 July. The current work focuses on the dynamic and thermodynamic processes that lead to the initial development and genesis of Dolly in the period from 1200 UTC 20 July to 0600 UTC 22 July.

3. Simulation of Dolly and model performance

a. Model configurations

This study uses the fully compressible Weather Research and Forecasting Model (WRF), version 3.0 (Skamarock et al. 2005). The model domain is triply
nested through two-way nesting with horizontal resolutions of 13.5, 4.5, and 1.5 km and mesh sizes of \(478 \times 361\), \(478 \times 361\), and \(757 \times 757\) grid points for the three meshes, respectively. The model has 35 levels with the model top at 10 hPa. The Grell–Devenyi ensemble scheme is employed in the outermost domain whereas no cumulus parameterization is used for the inner domains. For microphysics, the WRF single-moment (WSM) six-class scheme (with graupel) is used (Hong et al. 2004). For the planetary boundary layer, we use the Yonsei University (YSU) scheme (Noh et al. 2003).

The operational National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) analyses are used for the initial and boundary conditions of the WRF simulation. The initial sea level pressure and 200-hPa potential vorticity in the outermost domain are displayed in Fig. 3. The integration was conducted for 120 h beginning at 1200 UTC 20 July. In the first 12 h, the two inner domains were fixed. After that, the innermost domain moved to keep the model TC or its precursor in the center area of the domain. The middle domain was shifted accordingly.

**b. Performance of WRF simulation**

Figure 4 compares the track and intensity of model-derived Dolly to the best-track analysis by the National Hurricane Center (NHC). Both the track and intensity of the observed storm are well simulated by the WRF hindcast. From 1200 UTC 21 July to 1900 UTC 23 July, deviations between the observed and modeled track are less than 60 km (Fig. 4a). The model reproduced well the initial deepening of the central pressure before 2100 UTC 22 July, and both the simulated and observed storms reached their maximum intensity at around 1200 UTC 23 July (Fig. 4b).

The proper simulation of the track and intensity of Dolly (Fig. 4) implies that the developing process of Hurricane Dolly may have been well captured by the numerical model, on the basis of which the early development of Hurricane Dolly will be examined in detail. Following Tory et al. (2006b) and Dunkerton et al. (2008), the vorticity-centered\(^1\) domain will be used to discuss the

\(^1\) To minimize the impact of the small-scale deep moist convection on the location of the vorticity center, a filter based on 2D spectral decomposition (Lin and Zhang 2008) is performed on the vorticity field at the lowest model level (\(z = 188\) m) to filter the perturbations with horizontal scale less than 270 km. The place with the maximum vorticity in the filtered field is taken as the vorticity center.
early development of Dolly, rather than the circulation-centered domain widely used in the literature (e.g., Ritchie and Holland 1997; Davis and Bosart 2006; Sippel and Zhang 2008; Zhang and Sippel 2009). The presence of significant background mean flow (easterly with a velocity of about $27.4 \text{ m s}^{-1}$) significantly shifted the circulation center to the south of the vorticity center (Fig. 5), especially in the very early developing stage of Dolly (Fig. 5a). The dislocation of the circulation center from the true Lagrangian-invariant vorticity center was also noted in Dunkerton et al. (2008).

4. A three-stage genesis of Dolly

The current study focuses on the initial development of Dolly from 1200 UTC 20 July to 0600 UTC 22 July, after which the storm began its sharp intensification (Fig. 4b). Based on the sequence of key dynamic and thermodynamic processes that occurred in the inner-core area (area within a 90-km radius of the vorticity center), we partition the early development of Dolly into three consecutive stages: 1) the initial burst of convection; 2) stratiform development, dry intrusion and thermodynamic recovery; and 3) the reinvigoration of moist convection and rapid intensification. This three-stage genesis is broadly consistent with the three-phase development process described in Davis and Bosart (2001) and subsequently in Sippel and Zhang (2008). Based on the time evolution of the mean vorticity, maximum tangential wind, potential temperature perturbation, equivalent potential temperature at $z = 188 \text{ m}$, and the low- to midlevel relative humidity averaged over the inner-core area (Fig. 6), we can roughly denote the onset of stage 2 at around 1900 UTC 20 July and the onset of stage 3 at approximately 1200 UTC 21 July. The three stages of early development are in general also evident in the time–height diagrams of many other key variables in Fig. 7. Nevertheless, as will become clearer in the following discussions, the separation of key dynamic and thermodynamic processes between different stages may not be exactly sequential.

a. Stage 1: Initial burst of moist convection

First let us recall the distributions of the 1000-hPa vorticity, 400-hPa relative humidity, and 850-hPa wind vectors at the start of the WRF simulation shown in Fig. 8a. At the initial time, the trough axis of the easterly wave was located at around $83.3^\circ W$. Although there was no closed circulation in the low-level wind field, the precursor of Dolly can be identified as a mesoscale vorticity maximum in the northern part of the easterly wave trough region, which was centered at approximately $19.6^\circ N$, $83.3^\circ W$. Under the influence of the heat and moisture flux from the ocean, the low-level atmosphere was gradually destabilized. About two hours later, the mean convective available potential energy (CAPE) of the mesoscale vorticity disturbance was as large as 1600 J kg$^{-1}$ (Fig. 6d). Moreover, Fig. 1 shows that the precursor of Dolly was always situated in the pouch, which ensured the associated moistening concentration was not lost through shearing and dilution (Dunkerton et al. 2008). As a result, the low-to-midtroposphere relative humidity was quite high in the mesoscale vorticity anomaly (Figs. 8a,c). Abundant moisture and strong convective instability provided favorable conditions for moist convection to occur in the area of the mesoscale vorticity disturbance. From around 1400 UTC 20 July, strong and deep moist convection was initiated in the northern part of the easterly wave trough. Figure 7a shows that before the burst of convection, mean downward motion occurred from 3 km and above in the inner-core area of the disturbance. This weak mean downdraft could be induced by the model adjustment during the first few
hours, which is quite commonly observed when initializing a high-resolution model with coarse-resolution global analysis.

As a result of the convection that occurred in the cyclonic vorticity-rich environment, many intense vortices formed. Figure 9a displays the relative vorticity and vertical velocity in a vertical cross section at 15 km east of the disturbance center at 1600 UTC 20 July. The vorticity anomaly at 20 km north of the center of the incipient Dolly could be identified as a vortical hot tower (Hendricks et al. 2004) in which the vorticity maximum was located in the middle troposphere. As in Montgomery et al. (2006), the vorticity budget analysis in Fig. 9b shows that the stretching and tilting effects [the third and fourth terms on the right-hand side of Eq. (1) in section 5a] associated with deep moist convection were the main contributors to the vorticity enhancement of the VHT. Significant downdrafts and divergence from moist convection weakened the concentration of vorticity by convergence and contributed to a negative tendency through tilting at the early hours of simulation (Fig. 9b). In addition to this strongest VHT, there were many weaker vorticity anomalies in the inner core of the incipient Dolly, which could be decaying or emerging VHTs, most of which also had the maximum positive vorticity in the middle levels (Fig. 9a).

The statistics of the inner-core vorticity at this stage are exemplified in Fig. 9c through the distributions of the frequency of occurrence for values of vorticity as a function of height—that is, the contoured frequency by altitude diagram (CFAD) at 1600 UTC 20 July. The x axis denotes the value of relative vorticity and the shading indicates the frequency of the vorticity value shown on the x axis that occurred in the inner-core area. In agreement with Fig. 8a, the large positive vorticity anomalies appeared more frequently in the middle troposphere. However, the inner-core area-averaged vorticity was maximized at low levels (Fig. 9c) because more frequent negative vorticity anomalies were also produced through tilting and divergence effects in the middle levels (Figs. 9a,b), as was also the case in Davis and Bosart (2006).

Moreover, the thermodynamic structure of the incipient Dolly was also modified by intense convection. The significant modifications were warming in the upper troposphere and cooling in the lower troposphere as a result of upper-level latent heating and low-level evaporative cooling associated with the convective updraft and downdraft, respectively (Figs. 7a,c). Because of the vertical transport of moisture associated with convective

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\[^2\] CFAD was first used by Yuter and Houze (1995) to analyze the evolution of vertical motion and reflectivity in a midlatitude MCS and has recently been introduced to the study of TCs (e.g., Rogers et al. 2007; Nolan 2007; Zhang and Sippel 2009). In this study, CFAD was produced as in Nolan (2007). The values of vorticity at each altitude in a 90-km-radius circle around the center of the incipient Dolly were divided into 20 equal bins between the values shown on the x axis in the plot. To better view the large range of frequency values in these two-dimensional contour plots, we add 1 to the frequency values everywhere and then take the base-10 logarithm of the sum.

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updrafts, the relative humidity in most of the troposphere increased noticeably after 1400 UTC 20 July. However, this tendency was soon terminated and the relative humidity decreased gradually in the lower altitudes under the influence of the convective downdraft (Figs. 6b and 7c).

It is worthwhile mentioning that because of the “cold start” of the numerical simulation, the exact timing and burst of simulated convection discussed above might be somewhat artificial because in nature the convective burst might have occurred more continuously and earlier. Thus, the transition from stage 1 to the subsequent stage 2 could have been earlier and more seamless. However, the successful reproduction of the track and intensity of the storm as mentioned in section 3 (Fig. 4) implies that the subsequent evolution of the storm following the convective burst could still reflect the key dynamic processes in the early developing stage of Dolly.

b. Stage 2: Stratiform development, dry intrusion, and thermodynamic recovery

Following the initial convection burst phase, during which the low-level vorticity and maximum tangential velocity distinctly increased, there was a period of about 17 h from around 1900 UTC 20 July when the inner-core vorticity and maximum tangential velocity increased little (Fig. 6a). During this period, the thermodynamic structures in the inner core of the incipient Dolly underwent remarkable adjustment (Figs. 6b,c and 7b,c), accompanying the development of stratiform precipitation and subsequent mid-to-upper tropospheric dry air intrusion.

1) STRATIFORM DEVELOPMENT

Along with the convective bursts, mean CAPE averaged over the inner core of incipient Dolly was sharply reduced (Fig. 6d) and convective activity in the inner core was weakened (Fig. 7a). After around 1900 UTC 20 July, the deep convective towers concentrated near the leading edge of the cloud cluster (Fig. 10a) and the kinematic structures at the rear of the cloud cluster exhibited features associated with the stratiform rain process. From the vertical cross section of the reflectivity, storm-relative vertical circulation, horizontal divergence, and relative vorticity at 2100 UTC 20 July displayed in Figs. 10b,c, it can be seen that below the cloud deck the downdraft was dominant whereas upward motion was conspicuous above, and consequently the convergence and positive vorticity were distinct in the middle troposphere while the divergence occurred in the upper and low levels, as commonly observed in the stratiform precipitation region (Mapes and Houze 1995).

Not only the specific cross section displayed in Figs. 10b,c but also the inner-core averaged fields shown in Figs. 7a,b demonstrated distinct characteristics similar to that of stratiform dynamics. For example, the large mean reflectivity concentrated between 5 and 6 km after 1900 UTC 20 July (Fig. 7a) was consistent with the melting of slowly falling ice particles aggregating above the 0°C level. This feature resembles the typical mean profiles apparent when a group of convective cells in a cumulonimbus complex evolves from a highly convective state to a more stratiform state, as discussed by Yuter and Houze (1995). Accompanying the variation of reflectivity, the mean inner-core kinematic structures of incipient Dolly also changed—1) the low-level updraft disappeared and a mean downdraft emerged (Fig. 7a); 2) the low-level convergence associated with the convection was replaced by divergence, while distinct convergence appeared in the middle levels (Fig. 7b); and 3) the vorticity significantly increased in the middle...
troposphere after 1900 UTC 20 July (Fig. 7b). This sequence of events resembles that of a system dominated by stratiform dynamics as discussed by Houze (2004); it also occurred in the MCSs associated with a number of developing TCs observed during the Tropical Experiment in Mexico (TEXMEX) as illustrated by Raymond et al. (1998).

2) LOW-LEVEL RECOVERY

During the stratiform phase, the cold pool resulting from the previous convection bursts weakened gradually, most likely because of the sensible heat flux from the warm ocean (Figs. 6c and 7c). At the same time, the relative humidity below $z = 3$ km and the lowest-level equivalent potential temperature also rose slightly (Figs. 6c and 7c). After around 0200 UTC 21 July convection was active again (Fig. 7a). However, these convective activities were relatively shallow as compared with the previous convection. This might be attributed to the dry air intrusion in the middle troposphere after approximately 1900 UTC 20 July (Fig. 7c).

3) DRY AIR INTRUSION

As the pouch carried the incipient Dolly northwestward after 1200 UTC 19 July, it encountered a mid-to-upper tropospheric PV anomaly located in the northwest of the pouch (not shown). Consequently, the relatively dry air accompanying the subsynoptic PV anomaly invaded the pouch of Dolly in the middle troposphere. At 1200 UTC 20 July, the mid-to-upper tropospheric PV anomaly and the midlevel dry air were active respectively in the northwest and west of the mesoscale vorticity disturbance related to the incipient Dolly (Figs. 8a–c). By 0000 UTC 21 July, the PV anomaly and the dry air had both moved to the southwest of the incipient Dolly (Fig. 11a), while the midlevel vorticity of incipient Dolly was enhanced as a result of the convective burst and the following stratiform dynamical
processes (Fig. 7b). The PV anomaly and the enhanced midlevel vorticity of incipient Dolly (denoted by the circle in Fig. 11) led to the prevailing southwesterly in the southwest of incipient Dolly in the middle troposphere, which drove the dry air toward the inner-core area of Dolly, resulting in significant reduction of the midlevel relative humidity in the inner-core area of incipient Dolly as exhibited in Figs. 6b and 7c.

Along with the dry air intrusion, the sinking motion in the upper troposphere was enhanced and became dominant in the inner-core area (Fig. 7a). This might be associated with the upper-level convergence caused by outflows from the broader convection along the ascending branch of the easterly wave in the east of the inner core of incipient Dolly. The upper-level wind vectors and horizontal divergence and the vertical cross section of vertical velocity across the storm center at 0400 UTC 21 July displayed in Figs. 11d,g show that there was deep moist convection active in the east and northeast sides of the incipient Dolly center. Because of the midlevel drying and upper-level sinking (Fig. 11g), the convection that occurred after 0200 UTC 21 July was rather shallow and the updraft was confined below $z = 8$ km (Fig. 7a).

4) MID-LEVEL MOISTENING

Although the convection did not penetrate into the upper troposphere, it did contribute to the continuous humidification of the lower to middle troposphere after around 0200 UTC 21 July (Figs. 7a,c). Meanwhile, the evaporative cooling from the shallow convection also contributed to slight enhancement of the low-level cold pool (Figs. 6c and 7c). The low-level averaged potential

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**Fig. 8.** The NCEP GFS reanalysis data valid at 1200 UTC 20 Jul for (a) horizontal distribution of 1000-hPa relative vorticity (every $2 \times 10^{-5}$ s$^{-1}$), 850-hPa wind vectors, and 400-hPa relative humidity (shaded every 10%); (b) 200-hPa relative vorticity (shaded every $10^{-5}$ s$^{-1}$) and horizontal wind vectors; and (c) vertical distribution of the relative humidity (shaded every 10%) and vertical velocity (every 0.1 Pa s$^{-1}$) in the cross section along latitude 19.6°N. The circles in (a) and (b) and the × in (c) denote the position of the precursor of Dolly.

**Fig. 9.** (a) Vertical cross section of the relative vorticity (colored every $10^{-4}$ s$^{-1}$) and vertical velocity (contours with values of $-1.5, -1, -0.5, 2, 4, 8, 12$ m s$^{-1}$; negative values dashed) at 1600 UTC 20 Jul. (b) As in (a), but for the vorticity tendency induced by the stretching (colored every $10^{-6}$ s$^{-2}$) and tilting effects (contours with values of $-6, -4, -2, -1, -0.5, 0.5, 1, 2, 4, 6 \times 10^{-6}$ s$^{-2}$; negative values dashed). The cross section is located at 15 km east of the storm center and the x axis denotes the meridional distance from the storm center. (c) Contoured frequency–altitude diagrams for relative vorticity (x axis; unit = $10^{-5}$ s$^{-1}$) at 1600 UTC 20 Jul. Colors indicate the logarithmic values of the frequency of the vorticity value shown on the x axis occurring in the inner-core area. The dashed line denotes the mean relative vorticity averaged within a 90-km-radius inner-core area around the storm center inflated by a factor of 10 for clarity.
temperature and equivalent potential temperature were also further slightly reduced after the model-simulated Dolly made landfall on the Yucatan Peninsula at 0430 UTC 21 July (Figs. 6c and 7c). Three hours later, rapid midlevel moistening and low-level warming occurred as the incipient Dolly situated over the warm ocean again and the storm gradually transitioned into the next stage before rapid intensification.

In summary, the second stage features a period of adjustment that is different from classic postconvection recovery, in which downdrafts suppress convection until the low-level temperature and moisture fields recover and deep convection redevelops. In contrast, the thermodynamic adjustment and recovery during this intermediate stage was accompanied by the development of stratiform precipitation and mid-to-upper tropospheric dry air intrusion.

c. Stage 3: Reinvigorated moist convection and rapid intensification

Following the sequence of thermodynamic adjustment and recovery in stage 2 and re-emergence of the storm center over the warm ocean, convection was reinvigorated after 0800 UTC 21 July (Fig. 7a). Strong upward motion was again dominant in the inner-core area throughout the troposphere (Figs. 7a and 11b). Correspondingly, the divergence was noticeable in the upper levels (Fig. 11c). Because of the strong upward transport of the moisture through convection, most of the troposphere, especially the mid-to-upper levels, was further humidified (Figs. 6b, 7c, and 11b). Consequently, evaporative cooling and downward mass fluxes in the inner-core area of the incipient Dolly were weakened in comparison to the previous episodes (Fig. 12). Such a decrease in downdraft mass flux preceding the genesis of TC was also noted by Bister and Emanuel (1997) and Raymond et al. (1998). In agreement with the argument of Bister and Emanuel (1997) that the weakened downdraft is beneficial to the enhancement of the low-level convergence and vortex intensification, the low-level maximum tangential wind was evidently strengthened after 1200 UTC 21 July (Figs. 6a and 7b). As a result, more moist entropy would be extracted from the ocean to increase the inner-core equivalent potential temperature and thus conditional instability (Figs. 6c,d). Meanwhile, the original low-level cold pool diminished gradually as the surface circulation intensified (Fig. 7c).

After 1200 UTC 21 July, the lower-to-middle troposphere had been well humidified, with the mean inner-core relative humidity below 6 km greater than 80%. However, rapid intensification of the incipient Dolly vortex did not occur immediately as it did in Nolan (2007). This could be at least partially ascribed to the strengthened environmental vertical wind shear ($V_{12km} - V_{1.5km}$) (Fig. 6d). Although the shear averaged over the storm-centered domain with radius of 540 km was relatively weak (less than 9 m s$^{-1}$), it might be strong enough to impact the storm development in the period from around 1400 UTC 21 July to 0000 UTC 22 July according to recent studies of Gallina and Velden (2002) and Wong and Chan (2004). The delayed rapid intensification could also result from another episode of dry air intrusion in the mid-to-upper troposphere (Figs. 7c and 11c). This new episode of dry intrusion was associated with a strengthened...
southerly flow from a larger dry air pool over the Yucatan Peninsula at this time (Fig. 11c). This was further accompanied by enhanced upper-level convergence and downdraft in the upper troposphere above the inner-core area of Dolly (Figs. 7a and 11f), which further prevented the immediate development of sustained deep convection.

After 1800 UTC 21 July, the weakening of the dry intrusion (Fig. 7c) and reduction in vertical wind shear (Fig. 6d) made the environment favorable for the rapid development of the incipient Dolly with well-conditioned lower-to-middle tropospheric moisture and enhanced moist entropy in the low levels (Fig. 6c). Along with the intensification of the cyclonic circulation of Dolly at the middle troposphere, the midlevel dry air was completely absent from the inner-core area of Dolly. Subsequently, Dolly intensified to a category-2 hurricane at around 1500 UTC 23 July.

As in stage 1, the vorticity anomalies resulted from moist convection, many of which may be characterized as VHTs, were very active in the center area of Dolly (Figs. 7a and 11f), which further prevented the immediate development of sustained deep convection.

Figure 14a shows the relative vorticity in the cross section located at 87 km west of the storm center at 1500 UTC 21 July. It is obvious that most anomalies, including a VHT situated at approximately 20 km north of the storm center, were surface based. The vorticity tendency indicates that the significant contribution to
the enhancement of these anomalies was the stretching effect associated with the low-level convergence (Fig. 14b). Correspondingly, large values of the cyclonic vorticity appeared more frequently in the low levels instead of the middle troposphere (Fig. 14c). As the system evolved, these vorticity anomalies were gradually wrapped into the storm central area along with frequent vorticity aggregation (Figs. 13a,b). This phenomenon might be ascribed to the system-scale toroidal circulation induced by the macro effect of diabatic heating linked with VHTs as suggested by Hendricks et al. (2004) and Montgomery et al. (2006).

Figure 13c shows the tracks of three vorticity anomalies that first appear at 0304, 1034, and 2334 UTC 21 July, which will be referred to as the 03-UTC, 10-UTC, and 23-UTC anomalies, respectively. The aggregation of the 03-UTC and 10-UTC anomalies at about 1230 UTC 21 July followed by a localized deep convective burst formed a larger-area vorticity anomaly (see the rectangular box in Fig. 13a). This larger vorticity anomaly initially spiraled radially outward but later spiraled inward and eventually circled around the storm center at a radius of less than 50 km. The 23-UTC anomaly that first appeared northeast of the storm center, on the other hand, spiraled directly toward the storm center and finally circled around the storm center with a radius smaller than 50 km as well (Fig. 13c). Because of the convergence and aggregation processes, the sporadically and loosely distributed vorticity anomalies at 1500 UTC 21 July became tightly organized around the storm center and the typical horizontal scale of individual anomalies also noticeably increased by 0600 UTC 22 July (Figs. 13a,b).

As the small-scale vorticity anomalies aggregated and converged to the storm center, the anomalies with larger...
scales also underwent considerable variations. Figure 15 shows vorticity with horizontal scales between 50 and 150 km (called mesoscale here) superposed upon vorticity with scales larger than 150 km obtained by performing two-dimensional spectral decomposition on the vorticity field at $z = 188$ m (Lin and Zhang 2008). Comparison of Figs. 13a,b and 15b,g shows that the aggregated vortices displayed in Figs. 13a,b can be approximately described by the mesoscale vortices with scales from 50 to 150 km. At the beginning of the third stage starting from around 1200 UTC 21 July, the mesoscale vortices were loosely distributed and relatively

FIG. 14. As in Fig. 9, but for 1500 UTC 21 Jul. The cross section is located at 87 km west of the incipient Dolly center and the vertical velocity was contoured every 1.0 m s$^{-1}$ from $|w| = 0.5$ m s$^{-1}$.

FIG. 15. Evolution of the vorticity anomalies at $z = 188$ m centered on the incipient Dolly every 3 h from 1200 UTC 21 to 2100 UTC 22 Jul. Color shadings represent vorticity of the anomalies with the horizontal scales larger than 50 km but smaller than 150 km. Contours represent vorticity of the anomalies with the horizontal scales larger than 150 km (every $1.5 \times 10^{-4}$ s$^{-1}$). Axes are in km and easily tractable anomalies are numbered.
weak except for the anomaly denoted by number 1 (Fig. 15a). Meanwhile, the vortex with scales larger than 150 km was weak as well. Following the convergence and aggregation of small-scale vortices, five distinct mesoscale vortices gathered in the storm center area by 0300 UTC 22 July (Fig. 15f). Consistent with the assembly of these mesoscale vortices, the vortex in the larger scale (>150 km) was considerably strengthened. Three hours later, another mesoscale vortex appeared in the storm central area and the other vortices were arranged more tightly (Fig. 15g). Along with the merger and intensification of the mesoscale vortices, the primary larger-scale (>150 km) vortex was strengthened and became more symmetric (Figs. 15g–k). By 2100 UTC 22 July both the larger-scale and the 50–150-km-scale vortices were strong and had a well-defined axisymmetric structure in the storm center area (Fig. 15l). At around 0000 UTC 23 July, Dolly developed into a hurricane.

5. Sources of low-level vorticity: Top-down versus bottom-up

The analysis of the inner-core kinematic structures of incipient Dolly shows that the early development of Dolly took place in three stages: (i) a convective burst; (ii) stratiform development, dry intrusion, and thermodynamic recovery; and (iii) reinvigoration of convection and rapid intensification. Throughout these stages, both stratiform and convective dynamics were active, which is interesting because of their relationship to the competing top-down and bottom-up theories for TC formation (refer to section 1). In this section, relevant diagnostic analyses are carried out to further evaluate the role of top-down versus bottom-up thinking in the development of the incipient Dolly vortex.

a. Analysis of the source of the low-level vorticity

As the system evolved, the cloud cluster transitioned from a convective to stratiform dominant regime after 1900 UTC 20 July. The mean convergence averaged over the inner-core area of incipient Dolly maximized at the middle troposphere; correspondingly, the midlevel mean vorticity enhanced greatly (Fig. 7b). However, there is no evidence of downward extension of the midlevel mean convergence and vorticity that would have caused the intensification of the low-level vorticity. On the contrary, the low-level vorticity decreased slightly while the low-level flow transitioned from being convergent to divergent (Figs. 6a and 7b). From around 0200 UTC 21 July, the low-level vorticity was strengthened coincident with convection (Fig. 7a) and low-level convergence (Fig. 7b), indicating that this increase of low-level vorticity seems to be more attributable to the convergence associated with convection. Figure 16a displays the time–height diagram of the area-mean divergence, showing vertical vorticity only in the stratiform region in the storm-centered domain with a radius of 90 km, which further indicates that the midlevel convergence and vorticity did not extend downward to enhance the low-level vortex even in the stratiform precipitation area. That the low-level convergence and vorticity began

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4 The partition between stratiform and convection is conducted by comparing the statics of vertical motion and reflectivity fields. If the reflectivity exceeds 15 dBZ and vertical velocity is smaller than 1.5 m s⁻¹ within 5 km, that location is considered stratiform. The values of 15 dBZ and 1.5 m s⁻¹ are taken from Rogers et al. (2007).
to increase after 2200 UTC 20 July could be related to the shallow convection below the stratiform cloud deck resulting from the low-level moistening and surface thermodynamic recovery (Fig. 16b). There was also another brief episode of stratiform development right after the reinvigoration of convection at the start of stage 3 (Fig. 7b). There is also no traceable evidence of downward extension of the midlevel vorticity in the vertical profile of inner-core mean vorticity.

To understand the physical processes responsible for the spinup of the incipient Dolly vortex, a vertical vorticity budget averaged over the inner-core area of incipient Dolly was performed. Considering the translation of the system, the vorticity equation in a reference frame moving with the storm is adopted, which may be written as

$$\frac{\partial \zeta}{\partial t}_{SR} = -(V_h - C) \cdot \nabla_h (\zeta + f) - w \frac{\partial \zeta}{\partial z} - (\zeta + f) \nabla_h \cdot (V_h - C) - \left( \frac{\partial w}{\partial x} \frac{\partial v}{\partial z} - \frac{\partial w}{\partial y} \frac{\partial u}{\partial z} \right) + \frac{1}{p^2} \left( \frac{\partial \rho}{\partial x} \frac{\partial p}{\partial y} - \frac{\partial \rho}{\partial y} \frac{\partial p}{\partial x} \right) + \frac{\partial F_s}{\partial x} - \frac{\partial F_s}{\partial y}, \quad (1)$$

where $\zeta$ is the relative vorticity and $C$ is the moving velocity of the storm, which is determined by the displacement of the vorticity center; its mean value is approximately $-7.4$ and $3.1$ m s$^{-1}$ in the west–east and south–north directions, respectively. The subscript SR denotes that this term is the local vorticity tendency in a reference frame moving with the storm. The terms on the right-hand side of Eq. (1) represent contributions to the change of $\zeta$ due to horizontal advection of absolute vorticity, vertical advection, stretching, tilting, solenoidal effects, and subgrid-scale flux derivatives, respectively. The solenoidal term and the $x$ and $y$ components of the subgrid-scale terms generally yield a small contribution to the net vorticity tendency and will be ignored in Eq. (1) following Montgomery et al. (2006). It is worth mentioning that besides convection, boundary layer friction in a cyclonic vortex could slow down the flow (and thus reduce vorticity intensity), but on the other hand could enhance low-level convergence (e.g., section 5.3 of Holton 2004), which could lead to stronger stretching and convection.

Figure 17a displays the vorticity tendency resulting from the vertical advection of vorticity. Although the vertical advection of vorticity had a tendency to enhance low-to-midlevel cyclonic vorticity at the first convective burst stage and the following stratiform episode, the negative mean vorticity gradient in the inner core of incipient Dolly shown in Fig. 7b implies that the positive vorticity tendency in the low-to-mid levels of Fig. 17a mainly resulted from the upward transport of the large value of vorticity from the lower levels by the updraft. Therefore, the downward advection of the midlevel vortex, expected to be important in the top-down development of Bister and Emanuel (1997), could not have played a key role in the spinup of the low-level vortex of incipient Dolly.

Moreover, the vertical advection of vorticity was nearly cancelled by the tilting tendency (Fig. 17b). The reason
is that the sum of the tilting and vertical advection terms in Eq. (1) can be expressed as the divergence of a non-adve ctive flux term, that is, $-\nabla_h \cdot \{\vec{w}(\partial k \times \vec{V}_h)/\partial z\}$ (Tory and Montgomery 2008). As noted by Tory and Montgomery (2008), when posed in pressure coordinates, the vertical advection and tilting must cancel within zero vertical motion isopleths ($\omega = 0$). The vorticity tendency linked with the divergence of the nonadvective flux was rather small in the early development of Dolly (Fig. 17c) except for the period after 0000 UTC 22 July when the circle with the radius of 90 km around the storm center failed to enclose all the relevant convection.

Although there can also be significant cancellation between the horizontal vorticity advection and the stretching terms as noted by Haynes and McIntyre (1987), the stretching effect dominated over the horizontal vorticity advection in the inner core of incipient Dolly in the low levels (Figs. 17d,e). As a result, the mean vorticity tendency induced by the horizontal advection and stretching—that is, the divergence of the advective flux, $-\nabla_h \cdot [(\vec{V}_h - \vec{C})(\xi + f)]$ (Tory and Montgomery 2008)—was positive in the lower altitudes in the inner core of incipient Dolly (Fig. 17f) and was responsible for the spinup of the low-level vortex exhibited in Figs. 6a and 7b.

The vertical distribution of the mean inner-core vorticity shown in Fig. 7b demonstrates that the vorticity in the middle troposphere usually underwent an enhancement following the remarkable strengthening of the low-level vorticity. This coincided with upward extension of the stretching effect in Fig. 17f, implying that the increase of the midlevel vorticity resulted from the convergence that extended from low levels, which further indicated that the early development of Dolly first occurred in the low levels and could be best identified as a bottom-up process.

b. Tracking of surface circulation center and top-down thinking

It is possible to misinterpret the early development of Dolly as a top-down process if the incipient storm is tracked by the circulation center defined by closed streamlines (instead of the vorticity center, as discussed in section 3b). To illustrate that this might be the case, the mean vorticity averaged over the midlevel-circulation-centered domain with a radius of 90 km in the period from 1200 UTC 20 July to 0600 UTC 22 July is displayed in Fig. 7d. It can be found that the midlevel vorticity demonstrated a downward extension to the lower altitudes after being enhanced through the stratiform dynamics between 1900 UTC 20 July and 0000 UTC 21 July. The appearance of a top-down process in Fig. 7d could thus be an unfortunate consequence of tracking the initial disturbance with the circulation–streamline center; the center of this domain may not properly capture the vorticity features in the early development of Dolly (see section 3b).

6. Concluding remarks

Through a cloud-resolving WRF simulation, the early development of Hurricane Dolly (2008) is examined in detail in this study. Based on the sequence of key dynamic and thermodynamic processes that occurred in the inner core of incipient Dolly, three stages of early development of Dolly were identified: 1) an initial burst of deep convection; 2) stratiform development, dry intrusions, and thermodynamic recovery; and 3) reinvigoration of convection and rapid intensification. During stage 1, under favorable environmental conditions, a burst of convection led to the intensification of vorticity and formation of cold pools in the low levels. As CAPE was consumed, convective activity in the inner core of incipient Dolly weakened and the storm evolved into stage 2, which began with typical stratiform development and then the low-to-mid level moistening; however, the thermodynamic recovery was much prolonged because of midtropospheric dry air intrusion. In stage 3, as the lower and middle troposphere moistened, evaporative cooling and downdrafts associated with moist convection were considerably reduced, which is beneficial to reinvigoration of surface-based moist convection. Subsequently, small-scale positive vorticity anomalies resulting from moist convection converged into the center area of the storm in spiral tracks, which might be ascribed to the system-scale toroidal circulation induced by the macro effect of diabatic heating linked with convection (Montgomery et al. 2006). The convergence and accompanying aggregation of vorticity anomalies projected the vorticity into larger scales and finally led to the spinup of the system-scale vortex.

After the burst of convection in stage 1, the kinematic structure of simulated incipient Dolly resembled that of a system dominated by stratiform dynamics. There was also another brief episode of stratiform development right after the reinvigoration of convection at the start of stage 3. However, there was no traceable evidence of downward extension of the midlevel vorticity in the incipient Dolly. The vorticity budget analysis further indicates that the spinup of the low-level vortex of incipient Dolly can be mainly ascribed to the stretching effect related to the low-level convergence. Therefore, the intensification of the incipient Dolly vortex can essentially be categorized as a “bottom-up” process.

It is also found that because of the significant background flow, there is a distinct displacement between the
vorticity center and the circulation/streamlines center during the early development of Dolly. Tracking of the incipient Dolly using this circulation/streamline center would fail to capture the development of the initial storm properly and in turn could lead to misleading the relationship between the increase of low-level vorticity and the midlevel vortex in the stratiform rain region in the early development Dolly. However, although the current work clearly demonstrates that Hurricane Dolly was spawned in the “pouch” of an easterly wave and then took a bottom-up route to genesis, caution needs to be taken to generalize the findings from this single case to other events. It is likely that there may be different pathways to tropical cyclogenesis other than the protective pouch and/or the bottom-up process. For instance, there was no apparent protective pouch in the rapid genesis of Hurricane Humberto (2007) along the Texas coast (Zhang et al. 2009), even though its genesis appears to be bottom-up as well (Sippel and Zhang 2010).

It is worth mentioning that although the role of VHTs in TC genesis has been discussed considerably in recent studies (Hendricks et al. 2004; Montgomery et al. 2006), the evolution of individual VHTs or the associated vorticity anomalies in the early developing stage of TCs has not been examined in detail. Our preliminary results (not shown) indicate that in the development of the storm, some vorticity anomalies dissipated after the local burst of convection whereas many other anomalies lasted a considerably longer time. The long life period of the vorticity anomaly was attributed not only to the aggregation of vorticity but also to the triggering of convection bursts. Tracing of the vorticity anomalies indicates that the accumulation and release of CAPE and the increase and decrease of relative humidity usually occurred alternatively during the evolution of these smaller-scale vortices. The dynamic and thermodynamic features of these anomalies and their role in the development of TC and the eyewall formation are currently under further investigation and the results will be presented elsewhere.

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