

INTENSIFICATION OF AN ASYMMETRIC, SHEARED TROPICAL CYCLONE IN A WRF SIMULATION

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1. INTRODUCTION

Intensity forecasts have experienced little improvement over the past couple decades (Rappaport et al. 2009). Rapid intensification (RI) events are particularly problematic in that they are almost always missed by operational forecasts (Elsberry et al. 2007). Vertical wind shear of the environmental flow has been known to be generally detrimental to tropical cyclone intensification, but rapid intensification events involving highly sheared tropical cyclones have been observed and documented in the literature (e.g. Nguyen and Molinari 2012). Tropical Storm Gabrielle was one such case. Initially, the convection was displaced downshear-left of the center, but a new mesovortex formed adjacent to a deep convective cell and deepened 22 hPa in 2.5 hours. Further details regarding the life cycle and the short-term rapid intensification were discussed by Molinari and Vollaro (2010). A high-resolution model simulation of this event was performed to gain insight into the physical processes involved in asymmetric, sheared tropical cyclone intensification and the development of a downshear mesovortex.

2. MODEL SETUP AND METHODS

The Weather Research and Forecasting (WRF) model version 3.2 (Skamarock et al. 2008) was used to simulate the rapid intensification period of Gabrielle's life cycle. The simulation utilized four nested domains of 27-km, 9-km, 3-km and 1-km horizontal resolution. The 3-km domain spanned 1980 km x 1530 km, while the 1-km spanned 600 km x 600 km. The 27-km and 9-km domains were initialized at 1200 UTC 13 September, the 3-km domain was initialized at 1800 UTC 13 September, and the 1-km domain was initialized at 0000 UTC 14 September. The 1-km domain ran until 1500 UTC 14 September, while the remaining three domains ran until 0000 UTC 15 September. The National Centers for Environmental Prediction (NCEP) global forecast system (GFS) final (FNL) operational global analyses were used for initial conditions and boundary conditions.

The model physics parameterizations used were as follows: The Kain-Fritsch cumulus parameterization on the 27-km and 9-km domains (Kain and Fritsch 1993), the WRF Single Moment (WSM) Six-Class microphysics scheme (Hong and Lim 2006), the Dudhia shortwave

radiation (Dudhia 1989) and the rapid radiative transfer model (RRTM) longwave radiation (Mlawer et al. 1997) schemes, and the Yonsei University planetary boundary layer scheme (Noh et al. 2003).

The center of the simulated tropical cyclone on various height surfaces was defined by the pressure centroid using the procedure recommended by Nguyen et al. (2014). As described in the aforementioned paper, the pressure centroid method outperformed other center-defining methods by being able to: (1) place the TC center within the region of weak storm-relative wind; (2) produce a smooth track; and (3) yield a coherent vertical profile of tropical cyclone vortex tilt.

3. EVOLUTION OF THE SIMULATED TROPICAL CYCLONE

As in observations, the simulated tropical cyclone (TC) underwent moderate to strong ambient vertical wind shear of between $8\text{--}12\text{ m s}^{-1}$ from the west-southwest. Figure 1 shows the evolution of sea level pressure and simulated reflectivity at 1 km height during the 0200–0500 UTC 14 September period. There was a persistent and distinct azimuthal wavenumber-1 asymmetry in reflectivity, with much of it restricted to the downshear and left of shear quadrants of the storm. This is consistent with previous modeling (e.g. Braun et al. 2006; Riemer et al. 2010) and observational (e.g. Corbosiero and Molinari 2002; Reasor et al. 2013) studies of highly-sheared storms. Of particular interest was a small-scale, intense vortex (hereafter: mesovortex) that developed prior to 0200 UTC (Fig. 1a), intensified and revolved counterclockwise within the TC circulation (Fig. 1b–c), and then began to turn radially inward and merged with the TC circulation (Fig. 1d). During the 0600–1200 UTC time period (not shown), the TC became more axisymmetric.

Figure 2 shows the minimum sea-level pressure anywhere within the 1-km domain (blue line) and at the TC center as defined in the previous section (red line). The disparity between the two lines can be interpreted as a measure of the intensity of the mesovortex relative to its TC background state. By either measure of TC intensity, the simulated TC deepens significantly during this 6-hour time period despite strong ambient vertical wind shear. The mesovortex deepened by about 5 hPa between 0250–0350 UTC. At the end of this deepening period, the minimum sea level pressure of the mesovortex was 7 hPa lower than the sea level pressure at the TC center. This difference then gradually diminished with time as the mesovortex merged with the TC vortex.

The strong mesovortex developed within a tropical cyclone vortex that was tilted with height. Figure 3 shows the pressure and wind fields on both the surface

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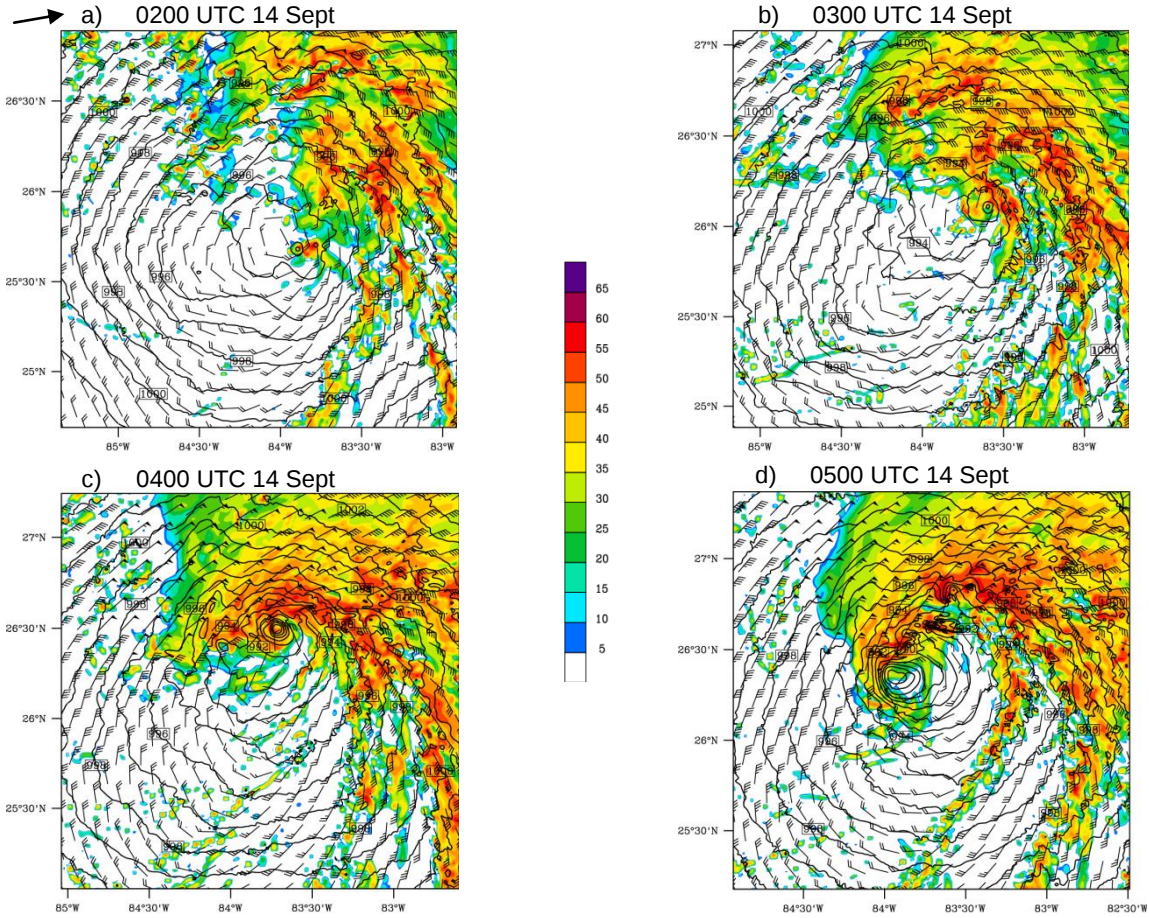


Fig. 1: Simulated reflectivity (shaded) at 1-km height, sea level pressure (contoured every 1 hPa), and 10-m winds. Each panel is centered on the tropical cyclone vortex center, as defined in Section 2. The approximate shear direction is shown at the upper-left.

and 8-km height surfaces, with the dots representing the TC center at various heights. The surface to 8 km TC vortex tilt settled in a stable, downshear-left (northeast) configuration throughout the simulation, consistent with previous theoretical (e.g. Reasor 2004) and observational (e.g. Reasor et al. 2013) work. At 0200 UTC (Fig. 3a), because of the TC vortex tilt, the mesovortex was located to the east-southeast of the TC surface center, but south of the TC 8-km center. Over the next couple hours (not shown), the mesovortex revolved cyclonically around the TC surface center and approached the TC 8-km center until becoming nearly aligned with the TC 8-km center by 0400 UTC (Fig. 3b). As the mesovortex was coming into closer alignment with the mid-upper level TC center during the 0245–0400 UTC period, the mesovortex intensified dramatically (Fig. 2). The significance of the alignment between the mesovortex and the broader TC mid-upper level vortex in the rapid intensification of the mesovortex remains a topic for future study.

Also notable is the clockwise curvature with height of the vortex tilt, which is persistent throughout the 0000–1200 UTC 14 September time period (not shown).

Similar curvature of vortex tilt has been observed in composites of airborne dual-doppler radar analysis of intense tropical cyclones (Reasor et al. 2013). How often this curved vortex tilt occurs in simulations of tropical cyclones in shear and in nature, and what physical processes are involved also remain topics for future investigation.

4. MESOVORTEX STRUCTURE

The mesovortex developed initially at around 0120 UTC 14 September to the south-southeast of the center of the tropical cyclone, adjacent to an intense convective cell. Beginning at around 0245 UTC, the mesovortex underwent a dramatic intensification. Figure 4a shows the relative vorticity and vertical motion fields at 1-km height at 0253 UTC, in a 50 km by 50 km domain centered on the mesovortex. The maximum relative vorticity at this time ($9.4 \times 10^{-3} \text{ s}^{-1}$) was located on the inside edge of an intensifying updraft with a maximum 1-km vertical velocity of over 4 m s^{-1} . This updraft initiated to the southeast of the mesovortex about 20 minutes prior, then intensified and wrapped

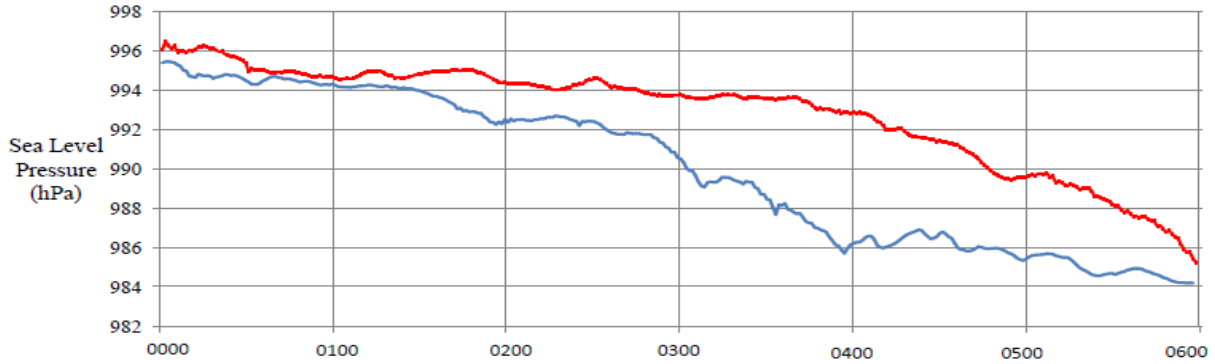


Fig. 2: Time series of the minimum sea-level pressure at the TC vortex center (red line) and the minimum sea level pressure within the model domain (blue line).

cyclonically around and inwards towards the mesovortex. In the 20 minutes following 0253 UTC, the 1-km maximum relative vorticity more than doubled to near $2.2 \times 10^{-2} \text{ s}^{-1}$, and the minimum sea level pressure fell 2.3 hPa (Fig. 2). At 0313 UTC (Fig. 4b), the mesovortex continued to remain on the inside edge of an intense convective updraft of over 6 m s^{-1} at 1-km height, while a downdraft of over 3 m s^{-1} developed to the southwest of the mesovortex. Throughout its life cycle, the mesovortex was typically located within the updraft region, but on the inward edge of the maximum updraft throughout the low-mid troposphere (not shown).

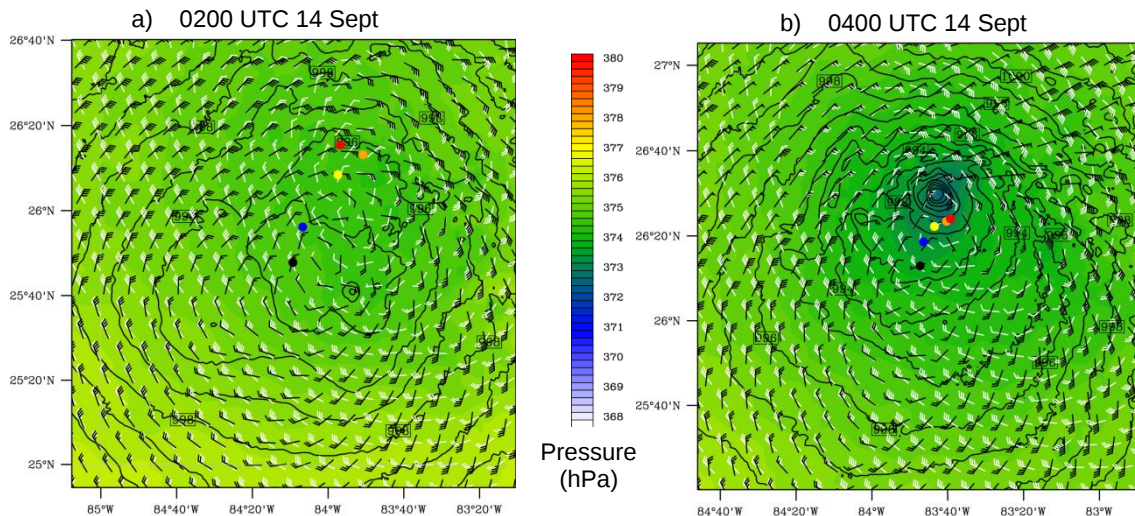
Figure 5a shows a vertical cross section through the mesovortex at 0303 UTC 14 September. The mesovortex was quite shallow and exhibited a bottom-heavy relative vorticity profile throughout most of its lifetime, with the region of $1 \times 10^{-2} \text{ s}^{-1}$ relative vorticity confined to the lowest 2 km. The intensification of the mesovortex began in the lowest 2-km adjacent to a

newly initiated, but shallow updraft. The horizontal scale of the mesovortex was quite small, on the order of 5 km across, and retained its small horizontal scale throughout its life. As in Fig. 5a, the high relative vorticity associated with the mesovortex was typically located either within the updraft but on the inward edge of the updraft core, or between the updraft and downdraft regions in the low-mid troposphere. The mesovortex was rarely, if ever, located directly within the strongest upward motion of the updraft core.

5. STRETCHING AND TILTING OF VORTICITY

The vertical vorticity tendency induced by the stretching and tilting processes were computed in the vicinity of the mesovortex following Montgomery et al. (2006). Figure 5b shows the stretching tendency at 0303 UTC 14 September. Note that although the mesovortex was not located within the updraft core, it

Fig. 3: Sea level pressure (contoured every 1 hPa), 10-m storm-relative winds (black wind barbs), 8-km pressure (color fill), and 8-km storm-relative winds (white wind barbs). The dots represent the TC vortex center positions starting from the surface (black) ascending in 2-km increments (blue, yellow, orange) up to the 8-km height (red).



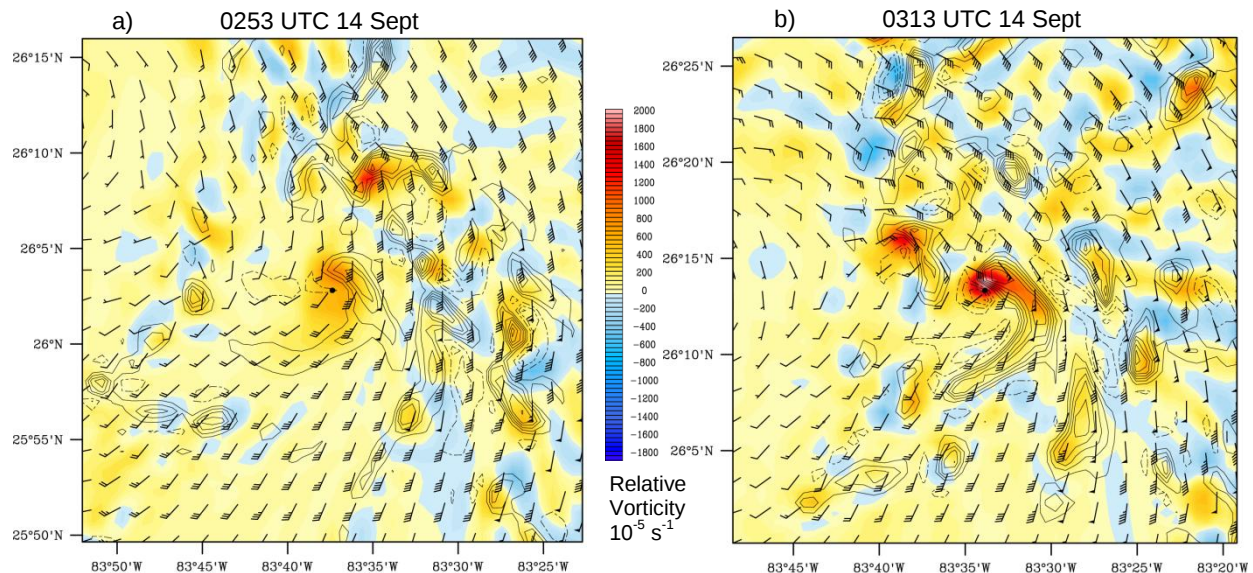


Fig. 4: Relative vorticity (color fill), upward vertical motion (solid contours every 1 m s^{-1} starting at $+1 \text{ m s}^{-1}$), and downward vertical motion (dashed contours every 1 m s^{-1} beginning at -1 m s^{-1}) at $z = 1 \text{ km}$.

was still located within a localized region of convergence and accelerating upward motion in the lower troposphere. This yielded stretching tendencies in the lowest 1 km exceeding $5 \times 10^{-5} \text{ s}^{-2}$. Large stretching of cyclonic vorticity was confined to the lowest 1 km in the immediate vicinity of the mesovortex. Above this shallow region, the stretching tendency changed sign, but was of lesser magnitude. This vertical couplet of very intense stretching of cyclonic vorticity in the boundary layer and weaker compression of cyclonic vorticity above was persistent throughout the 0230-0400 UTC time period, and appeared to be due to the outward (west to east) tilt of the updraft. Intense stretching of cyclonic vorticity occurs elsewhere within the tropical cyclone, but were much more transient in comparison to that associated with the mesovortex.

Fig. 5c shows the vertical vorticity tendency induced by tilting of horizontal vorticity at 0303 UTC 14 September. The convective updraft adjacent to the mesovortex acted to tilt horizontal vorticity into the vertical above the boundary layer on the western edge of the updraft and directly over the mesovortex. This is consistent with a typical tropical cyclone wind profile that decreases with height above the boundary layer. Fig. 5c shows the summation of the stretching and tilting contributions to the vorticity tendency. Just above the boundary layer, the tilting term appears to more than offset the weak compression of cyclonic vorticity, resulting in a net generation of cyclonic vorticity. The stretching process dominates in the boundary layer.

6. DISCUSSION

Vortical hot towers (VHTs), small-scale convective towers containing intense cyclonic vorticity, have been

hypothesized to play an important role in tropical cyclogenesis (e.g. Montgomery et al. 2006) and tropical cyclone intensification (e.g. Nguyen et al. 2008). In their cloud-resolving simulations, Montgomery et al. (2006) demonstrated that VHTs acquire vorticity via tilting of horizontal vorticity and by convergence and stretching of cyclonic vertical vorticity by the updraft. In particular, the generation of cyclonic vorticity by stretching dominated the generation of cyclonic vorticity by tilting near the surface. Our simulation shows a similar result: the stretching contribution to cyclonic vorticity generation dominates the tilting contribution in the lowest 1 km. The magnitude of stretching and its confinement to the near-surface boundary layer hints at an important role of friction in vortex spin-up, as suggested by Montgomery and Smith (2011). The mesovortex in this simulation remained shallow in depth with a bottom-heavy vorticity profile, but was very intense with maximum 1-km relative vorticity exceeding $2 \times 10^{-2} \text{ s}^{-1}$.

The mesovortex was rarely, if ever, collocated with the updraft core, but was instead located on the inward edge of the updraft. Recently, Hogsett and Stewart (2014) proposed the existence of supercell-like convective cells within the inner core of tropical cyclones that propagate inwards, contributing to intensification by enhancing diabatic heating within the radius of maximum winds. They hypothesized that these “cyclonic left-movers” would have the maximum stretching tendency nearly collocated with the maximum updraft, and the maximum tilting tendency on the inward edge of the maximum updraft, implying that the maximum cyclonic vorticity would likely also be on the inward edge of the maximum updraft. In our simulation, the mesovortex is indeed located on the inside edge of

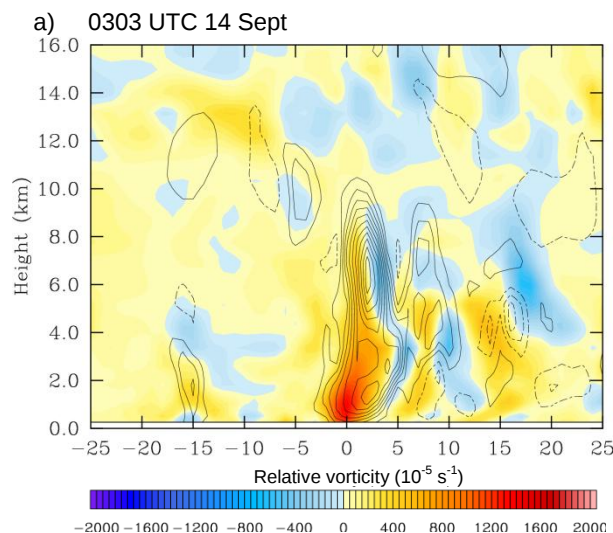


Fig. 5: West to east cross sections through the mesovortex. Color filled are (a) relative vorticity; (b) vorticity tendency induced by stretching; (c) vorticity tendency induced by tilting; (d) sum of stretching and tilting. Shown in all panels are upward vertical motion (solid contours every 1 m s^{-1} starting at $+1 \text{ m s}^{-1}$), and downward vertical motion (dashed contours every 1 m s^{-1} beginning at -1 m s^{-1}).

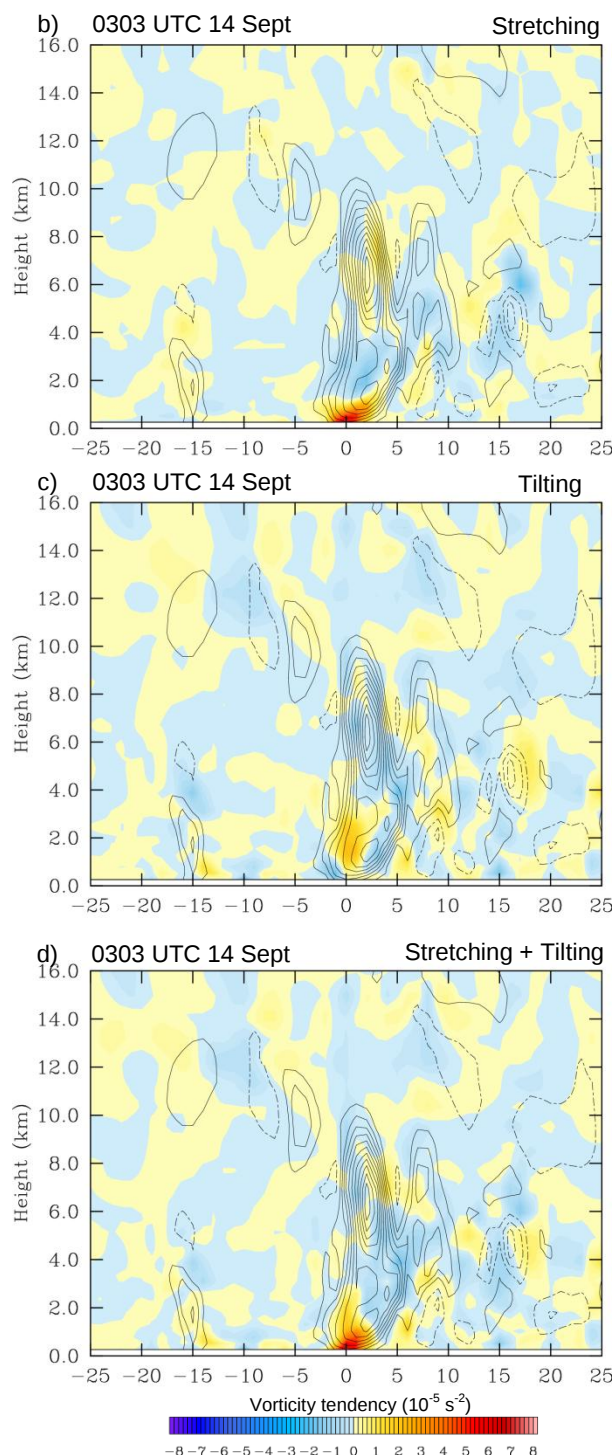
the updraft, and the mesovortex does propagate inwards. However, Hogsett and Stewart (2014) neglected the TC boundary layer for simplicity, and indeed recently Kilroy and Smith (2014) outlined the complications of introducing a realistic TC boundary layer wind profile to this conceptual model.

7. FUTURE WORK

Much work remains to be done to further understand the formation and intensification of the mesovortex, and its role in the intensification of the sheared tropical cyclone. The role of surface fluxes in enhancing boundary layer theta-e near the mesovortex will be assessed, both prior to mesovortex formation and during its rapid spinup. The mid-tropospheric humidity near the mesovortex will be evaluated to determine whether the enhanced moisture downtilt of the TC vortex (not shown) played a role in reducing entrainment of convective plumes, thereby enhancing tilting and stretching of vorticity associated with the mesovortex. The dynamics of the merger of the mesovortex and the TC vortex will be explored in more detail.

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