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• Original Paper •

Influence of Irregular Coastlines on a Tornadic Mesovortex in the Pearl River Delta during Monsoon Season. Part II: Numerical Experiments

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ABSTRACT

As demonstrated in the first part of this study (Part I), wind-shift boundaries routinely form along the west coast of the Pearl River Delta due to the land–sea contrast of a “trumpet” shape coastline in the summer monsoon season. Through multiple numerical simulations, this article (Part II) aims to examine the roles of the trumpet-shaped coastline in the mesovortex genesis during the 1 June 2020 tornadic event. The modeling reproduced two mesovortices that are in close proximity in time and space to the realistic mesovortices. In addition to the modeled mesovortex over the triple point where strong ambient vertical vorticity was located, another mesovortex originated from an enhanced discrete vortex along an airmass boundary via shear instability. On the fine-scale storm morphology, finger-like echoes preceding hook echoes were also reproduced around the triple point. Results from sensitivity experiments suggest that the unique topography plays an essential role in modifying the vorticity budget during the mesovortex formation. While there is a high likelihood of an upcoming storm evolving into a rotating storm over the triple point, the simulation's accuracy is sensitive to the local environmental details and storm dynamics. The strengths of cold pool surges from upstream storms may influence the stretching of low-level vertically oriented vortex and thus the wrap-up of finger-like echoes. These findings suggest that the trumpet-shaped coastline is an important component of mesovortex production during the active monsoon season. It is hoped that this study will increase the situational awareness for forecasters regarding regional non-mesocyclone tornadic environments.

Key words: mesovortex, tornado, land–sea contrast, coastline, monsoon

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Article Highlights:

- The land–sea contrast of a trumpet-shaped coastline is an important component for rotating storm development by producing quasi-stationary wind shift boundaries.
- The intersection zone of cold pool outflows and prevailing and sheared monsoonal onshore flows is characterized by local maxima of ambient vertical vorticity.
- Simulations of rotating storms that are associated with the trumpet-shaped coastline are highly sensitive to both environmental and storm-scale details.

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1. Introduction

Tornadoes that are associated with non-mesocyclone processes are typically weaker than mesocyclone (or supercell) tornadoes. Non-mesocyclone tornadoes on land are often called landspouts (Bluestein, 1985) and can also be occasionally destructive with an intensity of EF2 or EF3 rated on the enhanced Fujita (EF) scale (Wakimoto and Wilson, 1989; Yu and Zheng, 2020). They often appear associated with the meso-γ-scale (2–20 km; Orlanski, 1975) vortex (i.e., mesovortex; Schenkman and Xue, 2016) on the leading edges of squall lines or bow echoes, and sometimes form along surface convergent boundaries such as drylines and fronts (e.g., Lee and Wilhelmson, 1997a, b; Houston and Wilhelmson, 2007a, b; Schenkman et al., 2012). Previous studies have suggested difficulty in precisely forecasting the development of non-mesocyclone tornadoes as they usually develop rapidly and are often short-lived (Caruso and Davies, 2005). Most of these tornadoes have a life cycle of 5–10 min.

Compared to mesocyclone tornado environments that are usually characterized by large 0–1-km storm-relative helicity (SRH) and a low lifting condensation level (LCL), non-mesocyclone tornadoes frequently occur in environments with small values of vertical wind shear and SRH and/or relatively high LCL heights (Davies, 2006). The examined environments for three non-mesocyclone tornadoes in Caruso and Davies (2005) were all characterized by small near-storm 0–1-km SRH ($< 100\ \mathrm{m^2\ s^{-2}}$). Despite the great forecasting and warning challenges, some environmental ingredients may provide clues for assessing the potential for non-mesocyclone tornado processes, such as steep low-level lapse rates and high 0–3-km convective available potential energy (CAPE; Rasmussen, 2003) along a surface convergent boundary (Caruso and Davies, 2005). The presence of high low-level CAPE and steep lapse rates leads to a high potential for rapid vertical acceleration, thus favoring the vertical stretching process.

In contrast with mesocyclone tornadoes, non-mesocyclone tornadoes tend to develop during the early stages of updraft development (e.g., in-storm convective updrafts) while tornadoes associated with mesocyclones tend to be spawned during the mature stages of a supercell when the mesocyclone intensifies at lower levels (e.g., Lemon and Doswell, 1979; Burgess et al., 1993; Caruso and Davies, 2005). Supercell tornadoes are preceded by well-identifiable mid-level mesocyclones on Doppler velocity fields when significant downdrafts have organized in the rear-flank downdraft region. Non-mesocyclone tornadoes are found to be closely associated with low-level circulations that originate from the shear instability of surface convergent boundaries. Slow boundary-relative storm motion is typically associated with these types of tornadoes. When storms are positioned over a boundary, the transient vortex via shearing instability on the surface boundary is collocated with vigorous low-level updraft; thus, the environmental vertical vorticity tends to more deeply develop and sometimes strengthen to tornadic intensity (Wakimoto and Wilson, 1989).

Non-mesocyclone tornadoes are not unusual during the convective season in the Pearl River Delta (PRD, "trumpet" shape and concave toward the South China Sea), which is a tornado hotspot in Southern China (Wang, 1996; Fan and Yu, 2015; Zhou et al., 2020, 2022). For example, the tornadic event that occurred over the PRD estuary, as presented in the first part of this two-part series (Part I, Bai et al., 2024), was characterized by a mesovortex that developed near ground level. Part I presents the observational facts on the multiscale prestorm environments for a tornado that formed in the afternoon on 1 June 2020 when the South China Sea summer monsoon became active (Zhang et al., 2021). This tornado developed within a mesovortex at the southern-end of a quasi-linear convective system (QLCS) in the presence of weak tropospheric flows and low shear. Through a series of daily successive numerical simulations over the three June months from 2019 to 2021, Part I also demonstrated that the west coast of the PRD is characterized by a quasi-stationary surface convergent boundary that is generally parallel to the coastline. When storm-generated cold outflows interact with this boundary, a source of preexisting enhanced vertical vorticity appears to occur over the boundary intersection area (constituting a triple point). With the fine-resolution observations from an X-band phased-array radar that was located within only 6 km of this tornado, it was found that the initial finger-like echoes that were associated with an intruding gust front developed around the triple point. The finger-like echoes subsequently wrapped up into well-defined hook echoes (Fig. 1) with a mid-level mesovortex signature clearly identifiable on the Doppler fields. The tornadogenesis was preceded by the occurrence of this mesovortex. Based on the observational facts in Part I, the initial vertical vortex of the mid-level mesovortex is presumed to originate from the ambient vertical vorticity on the triple point.

An increased understanding of the environmental conditions that support regional tornadogenesis is an integral part of disaster prevention and mitigation for severe weather in the PRD region. The purpose of the second part of this study (Part II) is to complement the observational analysis in Part I and to explore the possible dynamics of mesovortex formation related to the influence of the monsoon, trumpet-shaped coastline, and storm cold outflows by convection-permitting numerical simulations. We are hopeful that this study will increase situational awareness for forecasting regional non-mesocyclone tornadic environments.

The remainder of this paper is organized as follows. Section 2 describes the model setup and methods. The simulated results from multiple sensitivity experiments are provided in section 3. Section 4 investigates the genesis of a mid-level mesovortex in the control experiment. The summary and final discussions are presented in section 5.

2. Model setup and methods

2.1. *Configurations of the control experiment*

To obtain insights into the formation processes of the tor-

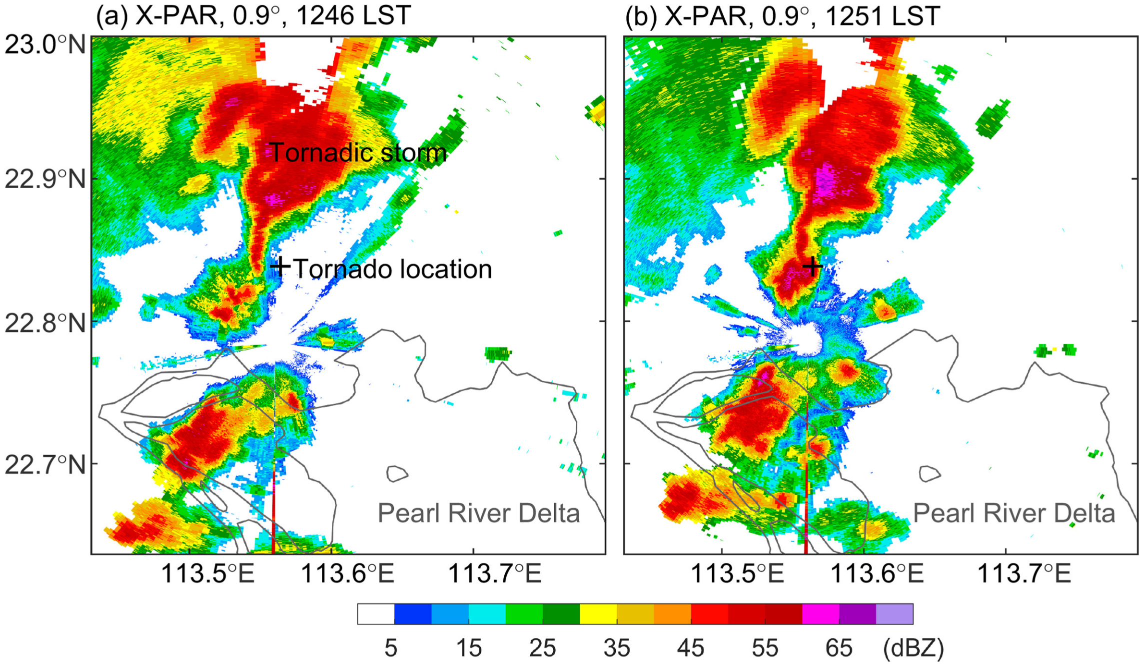

Fig. 1. Reflectivity obtained from the Nansha X-band phased-array (X-PAR) radar at the 0.9° elevation angle at (a) 1246 LST (Local Standard Time) and (b) 1251 LST on 1 June 2020. The black cross represents the reported tornado location.

nadic storm that was associated with multiple airmass boundaries, the fully compressible nonhydrostatic Weather Research and Forecasting (WRF) model, version 3.9.1 (Skamarock et al., 2008), was applied to run high-resolution, dynamically downscaled simulations. Four two-way nested domains were configured using a 1:3 ratio (Fig. 2a). By design, the horizontal resolutions were 9 km for the outermost domain and 0.333 km for the innermost domain. The vertical extent for the four domains included 50 stretched-grid levels up to 50 hPa on terrain-following coordinates. There were 15 vertical levels configured below 1.2 km above ground level (AGL). Figure 2c presents the land use types around the region of interest. The PRD is characterized by a megalopolis and thus its dominant land use type is "urban and built-up" on land. Domains d01, d02, and d03 were initiated at 0800 LST on 1 June 2020 while the innermost domain was initiated at 1000 LST. All domains were integrated until 2000 LST on 1 June 2020. The innermost model outputs were saved every 1 min.

Multiple sensitivity tests on microphysical and boundary process parameterization schemes, configuration in large eddy simulation (LES) mode, and the reanalysis data source for initial conditions were also conducted. The simulated results vary in the rain fields as compared to the observations. The selected simulation (hereinafter referred to as the control experiment) that is most comparable to the observed scenario was driven by the fifth generation of ECMWF atmospheric reanalysis (ERA5) data (Hersbach et al., 2020). The ERA5 data are available hourly with a horizontal resolution of 0.25°. The model lateral boundary conditions were updated at an interval of 1 h. The control (CTL) simulation was not configured in LES mode and thus the PBL parameterization scheme was activated using the Yonsei State University (YSU) boundary-layer scheme (Noh et al., 2003). Other physical parameterization schemes include the WRF single-moment 6-class (WSM6) microphysics scheme (Hong and Lim, 2006), thermal diffusion land-surface scheme, MM5 Monin-Obukhov surface-layer scheme, RRTM longwave radiation scheme (Mlawer et al., 1997), and Goddard shortwave radiation scheme (Chou and Suarez, 1994). The cumulus parameterization option was turned off. The remainder of the settings were configured in their default modes.

2.2. *Sensitivity experiment by artificial land accretion*

Based on the CTL experiment, a twin experiment was conducted to investigate the influence of the unique land–sea contrast on the formation of a rotating storm, as discussed in Part I. This sensitivity simulation was designed by changing the PRD sea surface to a land surface (hereinafter referred to as the CTL-land experiment). Over the PRD sea surface, the dominant land use category (LU_INDEX), land use fraction by category (LANDUSEF), and land mask (LANDMASK) were replaced with the values on the neighboring land surface (Figs. 2c, d). These modifications were conducted in the geographical file "geo_em.d01.nc" during the procedures of the WRF Preprocessing System (WPS). Other model settings were completely the same as those in the CTL experiment.

2.3. *Sensitivity experiment by cool bubble injection*

In addition to the twin simulations, another sensitivity simulation (hereinafter referred to as the CTL-bubble experiment) was conducted to investigate the role of storm cold outflow strength in the development of finger-like echoes over

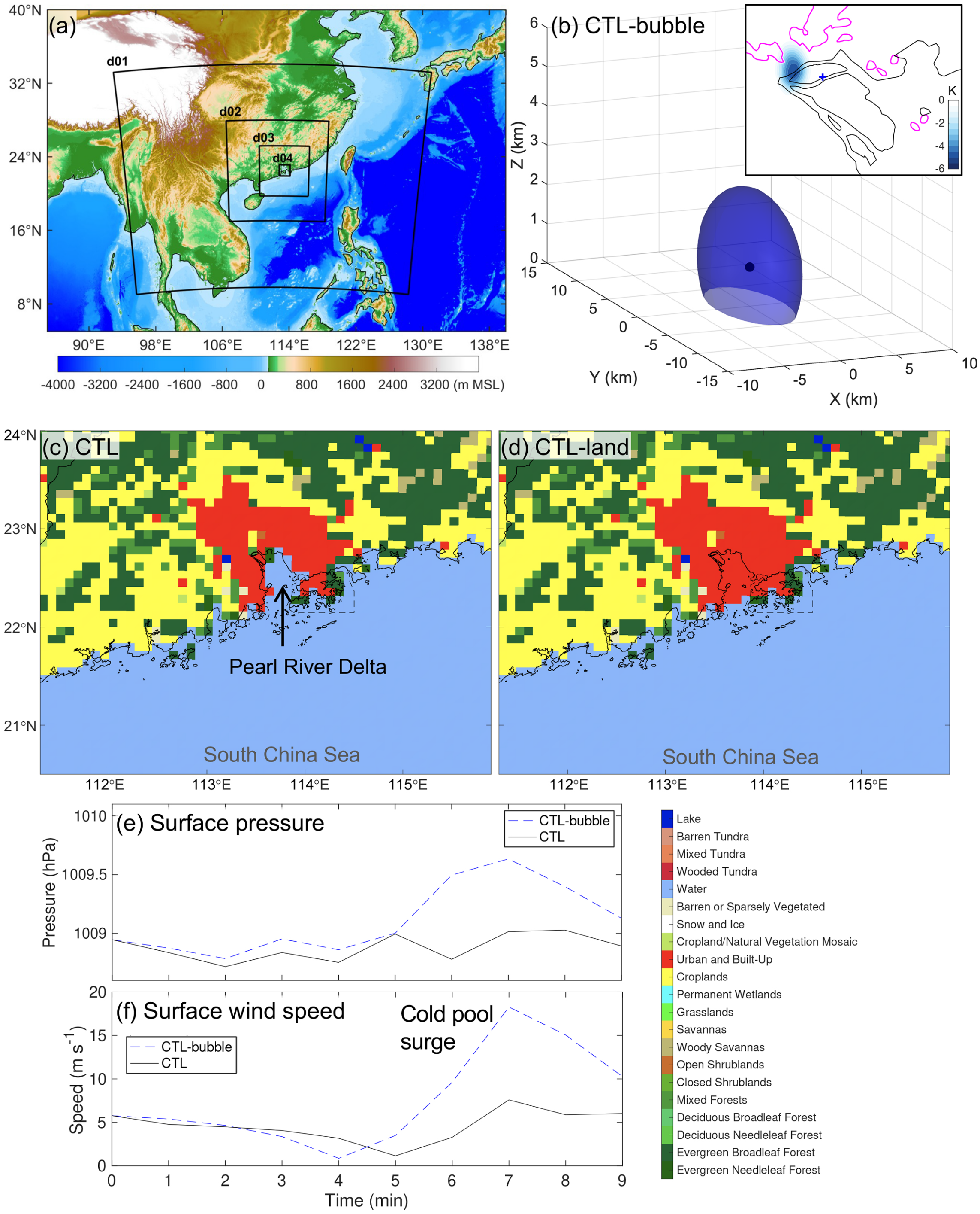

Fig. 2. (a) WRF domain configuration with terrain heights (shadings). (b) Schematic of the injected localized volume of negatively buoyant air in the CTL-bubble sensitivity simulation. This cool bubble was placed (22.7544°N, 113.455°E) to the west of the simulated finger-like echoes of Storm A as shown in Fig. 10b at 1220 LST. It is centered at a height of 1 km. The negative perturbation of potential temperature was maximized at the center (–10 K) and decreased to 0 K following a cosine function over a radius of 3.5 km, 6 km and 2 km in the zonal, meridional and vertical directions, respectively. The difference in the near-surface temperature between the CTL-bubble and CTL experiments at 1221 LST is also shown in the upper-right corner for reference. Reflectivity on model level 5 is contoured at 40 dBZ in magenta. (c) Land use types of the CTL experiment that represent the realistic topography (interpolated from the outermost WRF domain) and (d) the CTL-land experiment in which the PRD sea surface is replaced by the land surface. Time series of (e) surface pressure and (f) surface wind speeds for the CTL-bubble (blue) and CTL (black) experiments are plotted since 1220 LST. The selected location is marked by the cross as shown in the inset of panel (b).

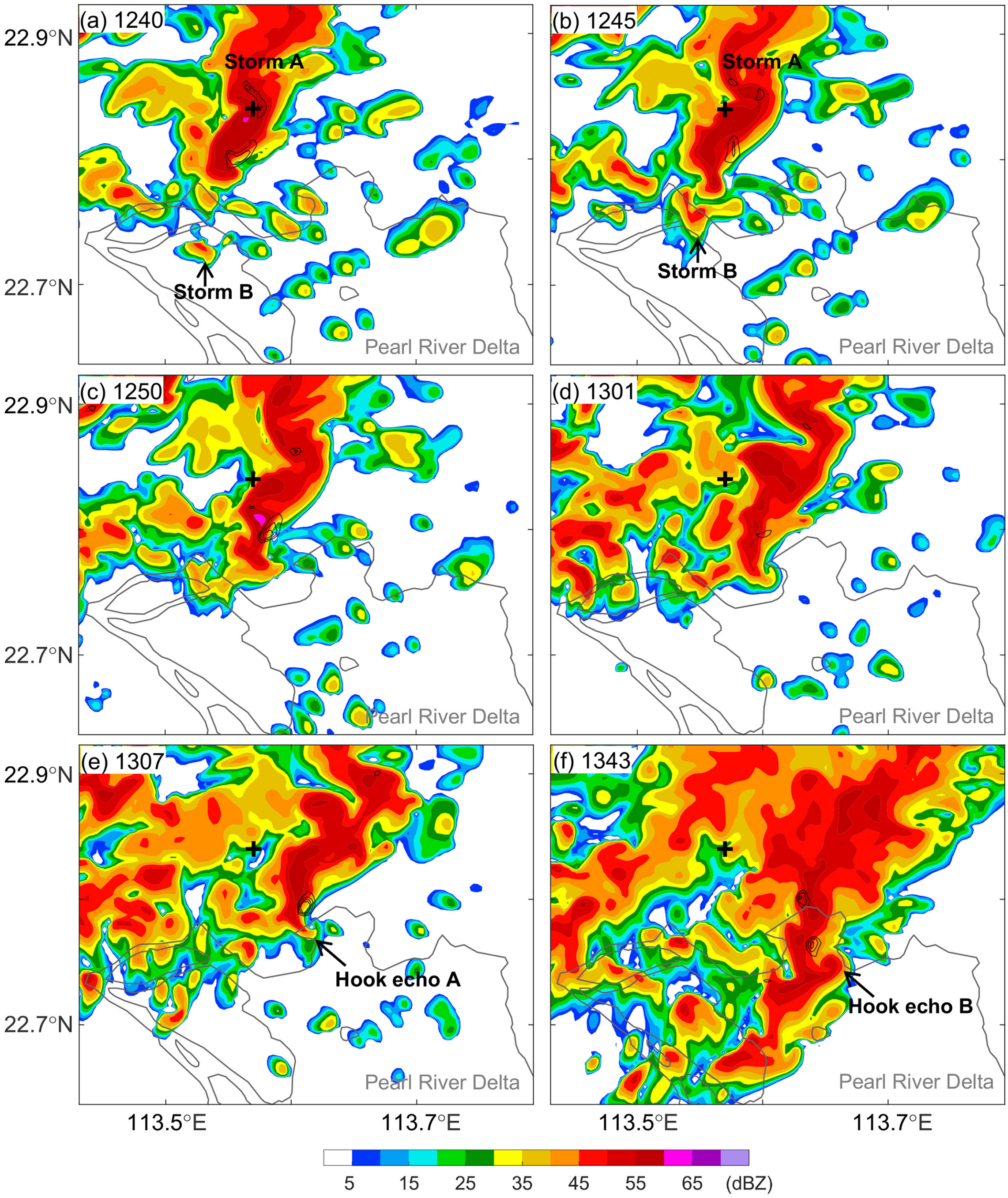

Fig. 3. Simulated reflectivity in the CTL experiment at the level of approximately 300 m above ground at different times (LST). The updraft helicity is contoured in black from 400 $m^2 s^{-2}$ at an interval of 200 $m^2 s^{-2}$. The black cross denotes the approximate location of the observed tornado.

the boundary intersection zone as discussed in Part I. A localized volume of negatively buoyant air was placed to the west of the simulated finger-like echoes by modifying the air temperature and temperature tendency in the innermost WRF restart file of the CTL experiment at 1220 LST (a schematic is presented in Fig. 2b). This cool bubble was centered at (22.7544°N, 113.455°E) with a height of 1 km. The negative perturbation of potential temperature was maximized at the center with a magnitude of −10 K, which decreased to 0 K following a cosine function over a radius of 3.5 km, 6 km and 2 km in the zonal, meridional and vertical directions, respectively. Other settings are the same as the CTL experiment. This type of method, achieved by directly modifying air temperature, has been widely applied in idealized simulations (e.g., Bryan and Fritsch, 2002; Markowski, 2020). By modifying the air temperature, convection initiation is typically accomplished via a warm bubble while a cold pool can be generated by adding a cold blob in the initial condition. The associated adjustments of other meteorological variables such as pressure, winds, and specific humidity

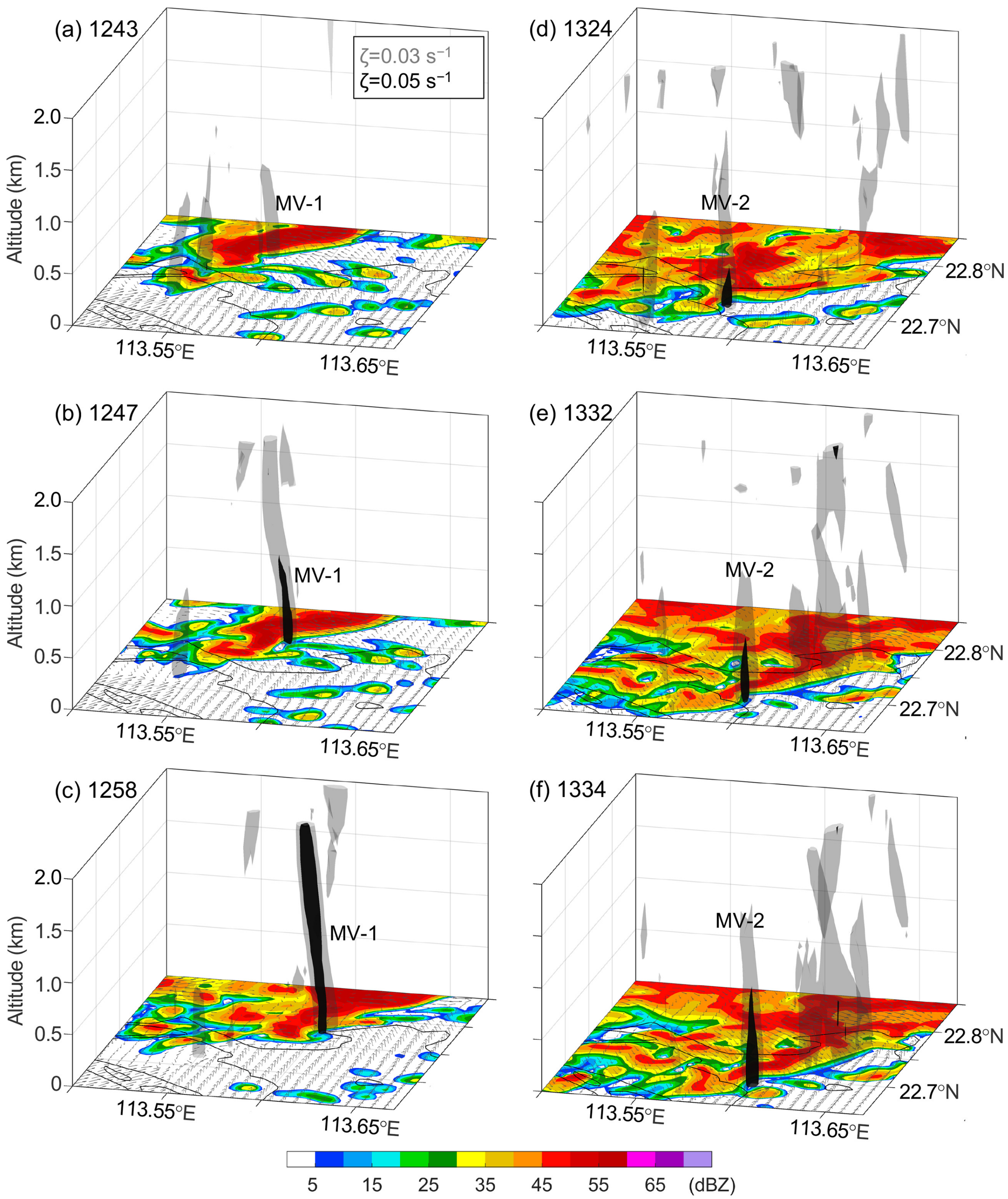

Fig. 4. Three-dimensional isosurfaces of 0.03 s^{-1} (gray) and 0.05 s^{-1} (black) vertical vorticity valid at different times (LST) on 1 June 2020 from the WRF d04 simulations. The simulated reflectivity and horizontal winds at model level 5 are also shown at the bottom for reference. The columns of enhanced vertical vorticity labeled MV-1 and MV-2 represent the mesovortices described in the text.

are expected shortly after model integration. In the current case, the simulated results present changes in a limited zone around the finger-like echoes because the modification of low-level air temperature was conducted in a localized region.

3. Simulated rotating storms from numerical simulations

3.1. *Storm-scale overview in the CTL experiment*

In this section, the general evolutions of simulated

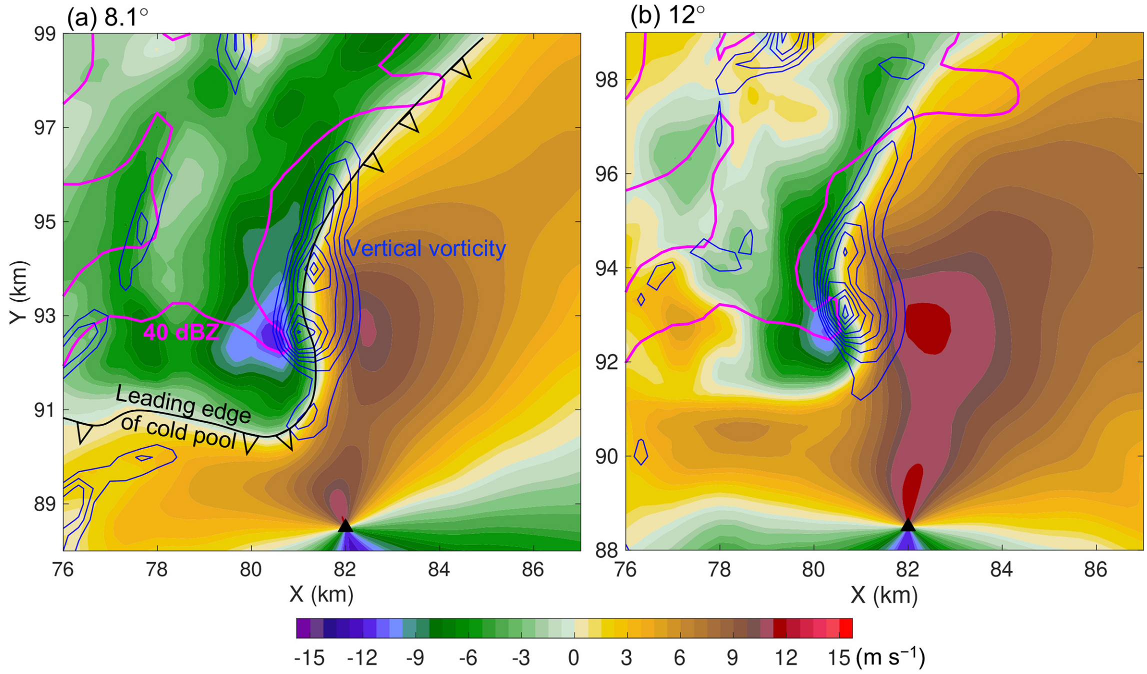

Fig. 5. Simulated radial velocity and reflectivity at the (a) 8.1° and (b) 12° elevation angle from the virtual radar (black triangle) at 1301 LST. Reflectivity is contoured at 40 dBZ in magenta. The vertical vorticities at (a) level 3 and (b) level 8 above ground are contoured in blue from 0.005 s^{-1} at an interval of 0.004 s^{-1}. The outflow boundary in panel (a) appears as a curve with triangles.

storms in the CTL experiment are discussed. To directly compare with the observed storm structures, especially the hook echo signatures (Markowski, 2002), the simulated low-level reflectivity is presented (Fig. 3). Near the location of the realistic tornadogenesis (refer to the black cross in Fig. 3), a simulated well-defined hook echo signature was located in the southern-end part of a storm (labeled "Storm A") since approximately 1240 LST. In the following 30 min, the appearance of the developing hook echoes becomes clearer (Fig. 3e).

Given that a model grid spacing of 0.333 km can explicitly resolve convective updrafts, the updraft helicity (UH; Kain et al., 2008) was calculated to assess the mid-level rotating updrafts within storms. Here, the UH was computed by vertically integrating the vertical component of helicity from 2 to 5 km AGL. Around the hook echo A, distinct local maxima of UH values were recognized, indicating the presence of a rotating storm (black isopleths in Fig. 3e). Similar to the observed storm merger, a merger process also occurred in the simulation. As shown in Figs. 3a–d, Storm B, previously located to the south of Storm A, propagated toward the northeast and merged with the hook echoes of Storm A at 1250 LST. After the disappearance of this supercell-like structure, another distinct hook echo signature (labeled "Hook echo B") with enhanced UH values was identified, nearly at the same location in the following 30 min (e.g., Fig. 3f). These two simulated hook echo signatures are consistent with those described in the observational analysis in Part I.

Near the two hook echo signatures, two columns of enhanced vertical vorticity developed as indicated by the black isosurfaces labeled MV-1 and MV-2 in Fig. 4. The enhanced vertical vorticity of MV-1 (with a value of 0.05 s^{-1}) started from the ground and subsequently reached an altitude of 5.5 km AGL after 1250 LST (Figs. 4a–c). These vortex signatures are representative of meso-γ-scale vortices rather than tornadoes considering that a grid spacing of 0.333 km can hardly resolve a tornado vortex. To directly compare the rotation with radar observations, a virtual phased-array radar was placed to the south of the simulated hook echo A. Figure 5 shows that the radial velocity pattern sampled by this virtual radar is comparable to that by the X-PAR during this event (Part I). Consistent with the observed mesocyclonic signature, the simulated radial velocities present an evident couplet with a core diameter of approximately 2 km (Fig. 5). This simulated mesocyclonic signature is generally confined to the layer below 5 km AGL. Considering that the occurrences of simulated and observed supercell-like storms are in close proximity in both time and space, the authors believe the model has faithfully reproduced the general physical processes of rotating storm formation.

3.2. *Simulated results with fake land in the PRD*

Figure 6 presents the comparisons of low-level reflectivity and dynamic fields between the CTL and CTL-land experiments. With fake land over the original PRD sea surface, the CTL-land experiment failed to generate any mesovortex and supercell-like storm (e.g., Storm A in Fig. 6a). In the absence of the downward branch of sea-breeze circulation, the fake land area was characterized overall by southwesterly

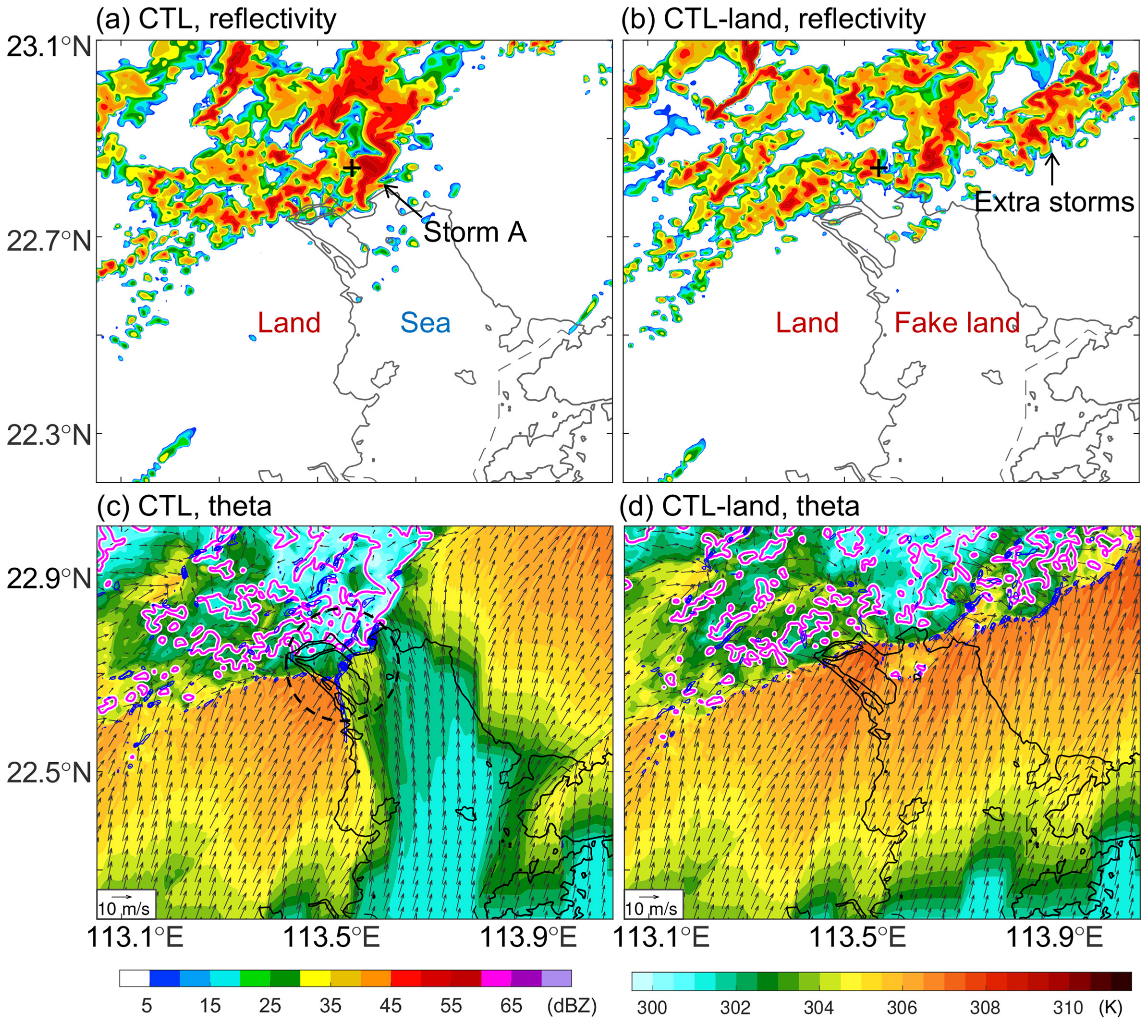

Fig. 6. Comparisons of the simulated reflectivity on model level 5 at 1300 LST on 1 June between the (a) CTL and (b) CTL-land experiments. Respective comparisons between the simulated potential temperature (shaded) and horizontal winds (vectors) on model level 3 are presented in panels (c) and (d). The simulated reflectivity is contoured at 40 dB*Z* in magenta. Vertical vorticity is contoured from 0.005 s^{-1} at an interval of 0.004 s^{-1} in blue. The dashed circle in panel (c) marks the location of the triple-point zone.

monsoonal flows at low levels and thus no triple point was expected, which was in contrast with the realistic scenario (Figs. 6c, d). Additionally, in the absence of a PRD sea surface, extra storms developed to the east of the previous Storm A (Fig. 6b). Without the obstruction of the onshore southeasterlies from the original PRD sea surface, the storm-generated cold outflows propagated faster toward the east, which proved responsible for the extra storms in the CTL-land experiment (Fig. 6d). Meanwhile, the convergent boundary formed by the storm cold outflows and the onshore flows was located relatively far from the preexisting storms. The resultant displacement between preexisting storms and the enhanced vertical vorticity along the convergent boundary would make it difficult to develop mesovortices.

In the current case, the presence of land–sea contrast of the trumpet-shaped coastline has decelerated the westerly components by at least 4 m s^{-1} over the northern part of the PRD sea surface (Fig. 7). The twin experiments demonstrate that the trumpet-shaped coastline helps to modify the ambient

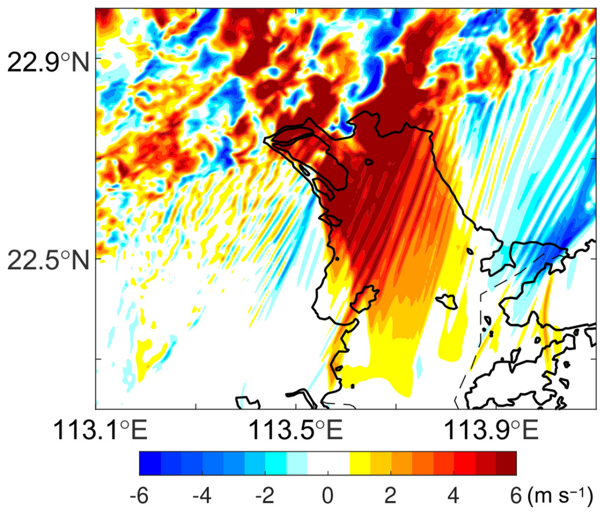

Fig. 7. Differences in the *u*-wind components on the lowest model level at 1300 LST on 1 June between the CTL-land and the CTL experiments.

vertical vorticity budget by perturbing the low-level prevailing monsoonal flows. Such topographically induced perturbations routinely produce surface airmass boundaries in a relatively fixed area. In the presence of other surface boundaries, such as storm-generated outflow boundaries or fronts, the resultant triple point would be beneficial to the development of rotating storms. As proposed in Part I, results from the twin experiments suggest that the trumpet-shaped coastline does indeed play an important role in the regional severe weather.

3.3. *Characteristics of simulated convergent boundaries and finger-like echoes*

This section provides an overview of the evolution of low-level features that are considered important for the genesis processes of mesovortices in the CTL experiment. The observational evidence discussed in Part I has indicated that a mesovortex formed at the tip of the finger-like echoes over the triple-point zone. In the CTL experiment, the simulated finger-like echoes of Storm A were located near the triple point (denoted by the dashed circle in Fig. 8a). This triple point was generated by the convergence of three types of low-level air flows that included storm-generated cold pool outflows (COF), southwesterlies (SW) on the land sides, and southeasterlies (SE) over the PRD sea surface (Fig. 8b). The prevailing monsoonal southwesterlies traveled from the cool sea surface to the warm land surface. These southwesterlies were characterized by higher potential temperature that thermally contrasted with the sheared monsoonal southeasterlies over the PRD sea surface and the nearground cold pool outflows that were generated by the preceding storms.

As demonstrated by the long-term numerical simulations in Part I, the land–sea contrast associated with this unique topography generates a meridional surface convergent boundary that is generally parallel to the western PRD coast (Fig. 8a). In the afternoon, the downward branch of the sea breeze circulation contributes to an easterly tendency of the wind component on the sea side of the west coast. On the other hand, greater friction is expected for the low-level airmasses on the land side due to the surface roughness contrast. The warmer land surface during the daytime also tends to decelerate the low-level flows because the heated land strengthens the turbulent exchanges of momentum in the boundary layer. In this case, the heated land surface perturbed the relatively cool maritime airmasses to favor the development of horizontal convective rolls (HCRs; refer to the band-organized vertical velocity in Fig. 9a). These HCRs intersected with the preexisting meridional surface boundary, producing some local maxima of enhanced vertical vorticity and convergence along the boundary (refer to the thin blue isopleths in Fig. 9).

Closer inspection of the simulated finger-like echoes agree with the observations in that they formed on the southern-end part of Storm A near the triple point (Fig. 8a). Recalling the observational analyses based on the X-band phased-array radar and surface weather stations, the realistic mesovortex and triple-point convergence were located in close proximity to the tip of the finger-like echoes (e.g., inset of Fig. 8a). As suggested by the CTL experiment, the triple point was

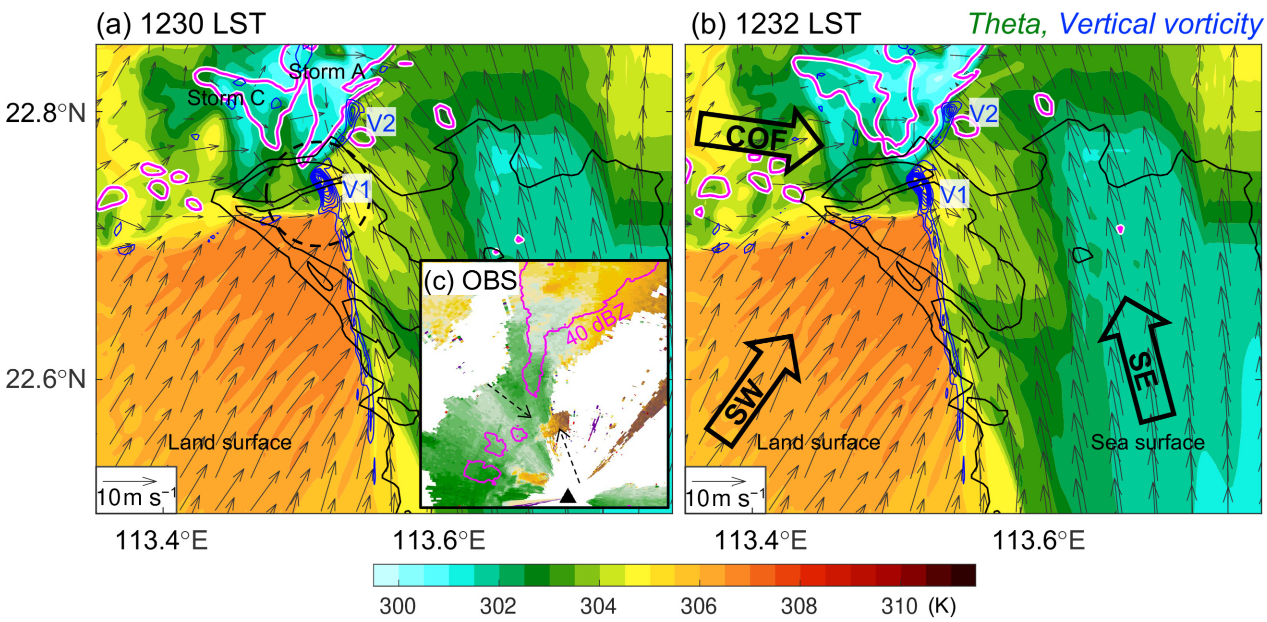

Fig. 8. Potential temperature (shaded) and horizontal winds (vectors) on model level 3 above ground at (a) 1230 LST and (b) 1232 LST. The vertical vorticity on this level is contoured from 0.005 s^{-1} at an interval of 0.004 s^{-1} in blue, and the reflectivity is contoured at 40 d*BZ* in magenta. The dashed circle in (a) marks the location of the triple-point zone. Vertical vorticity maxima are labeled V1 and V2, respectively. Panel (c) in the bottom-right corner of panel (a) shows the observed radial velocities (shaded; color scales are the same as that in Fig. 5) and reflectivity (magenta) at the 0.9° elevation angle of X-PAR at 1245 LST on 1 June 2020.

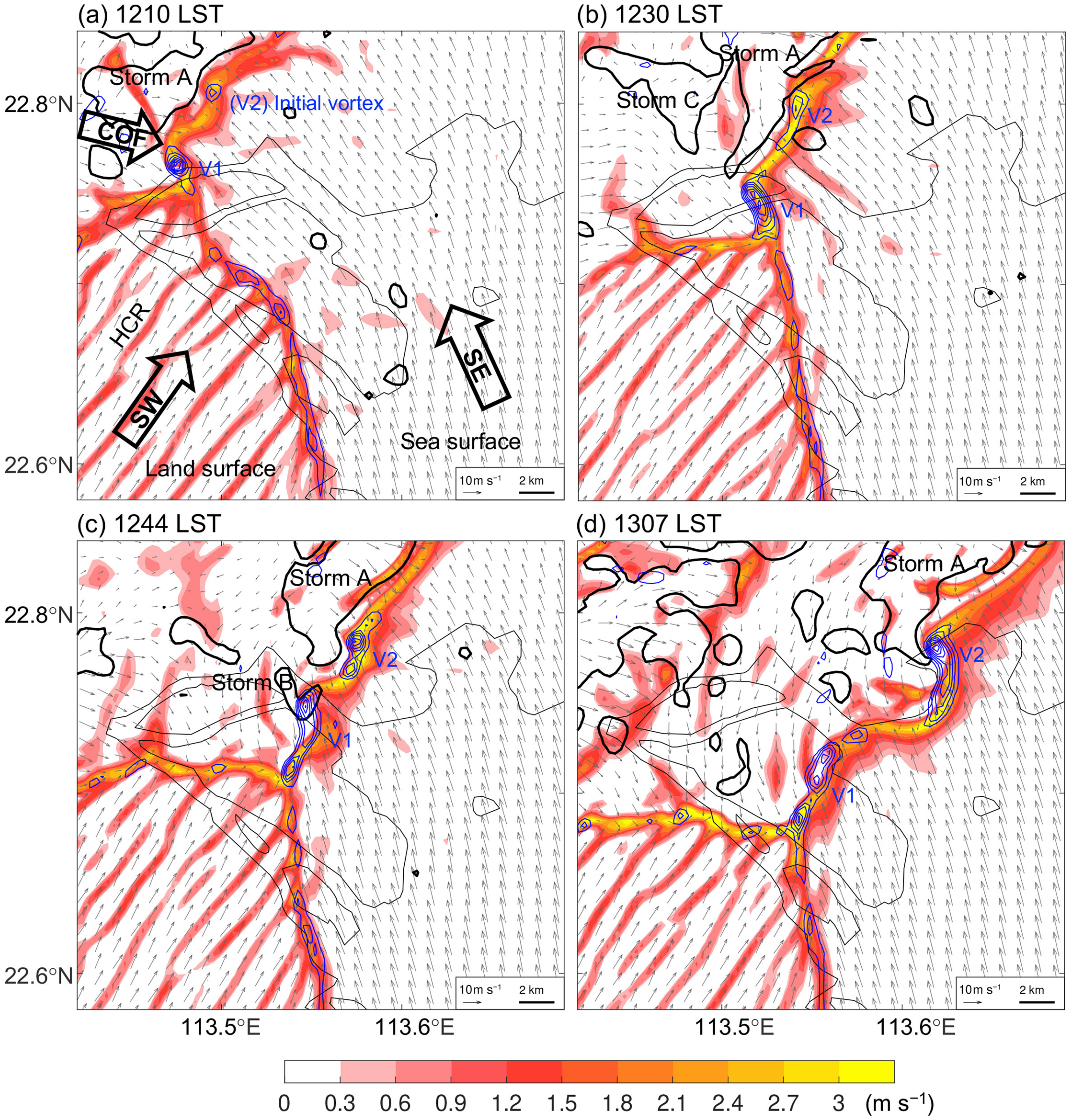

Fig. 9. Vertical velocity (shaded) and horizontal winds (vectors) on model level 3 above ground. The simulated reflectivity is contoured at 40 dBZ (heavy black isopleths) and the vertical vorticity is contoured from 0.005 s^{-1} at an interval of 0.004 s^{-1} in blue. The enhanced vertical vorticity zones are labeled V1 and V2.

characterized by persistent local maxima of ambient vertical vorticity near the ground (e.g., vortex V1 in Fig. 8). Further investigation suggests that the finger-like echoes were triggered by the enhanced cold outflow surges by the upstream storm (Storm C in Fig. 9b). The simulated wind fields and associated storm morphology resemble the radar observations and the analyzed low-level winds (dashed arrows in the inset of Fig. 8a). In comparison to the observations of the low power phased array radar, the simulated triple point appears as an evident signature of a radial velocity couplet, even in clear sky conditions (Figs. 10a, b). Given the spatial collocation between the triple point and the realistic tornadic mesovortex, the preexisting ambient vertical vorticity over the triple point is presumed to be the initial vortex for the genesis of the realistic mesovortex.

Different from the observations, a reflectivity wrap-up process (i.e., mesovortex formation) did not occur on the simulated finger-like echoes (Fig. 8b). Considering the presence of preexisting ambient vertical vorticity maxima over the triple point, the authors hypothesize that the wrap-up failure was likely a result of limited forced lifting provided by the cold outflow surges from the west. In the CTL-bubble sensitivity experiment, characterized by an injected volume of cold air as described in section 2, the cold pool surges to the west of the finger-like echoes were strengthened (Figs. 2e, f). Figure 10 presents a comparison of simulated radial velocity between the CTL and CTL-bubble experiments around Storm A. The injected cold air volume between Storm C and Storm A produced greater northwesterly components toward the triple point zone (represented by V1 in Fig. 10c),

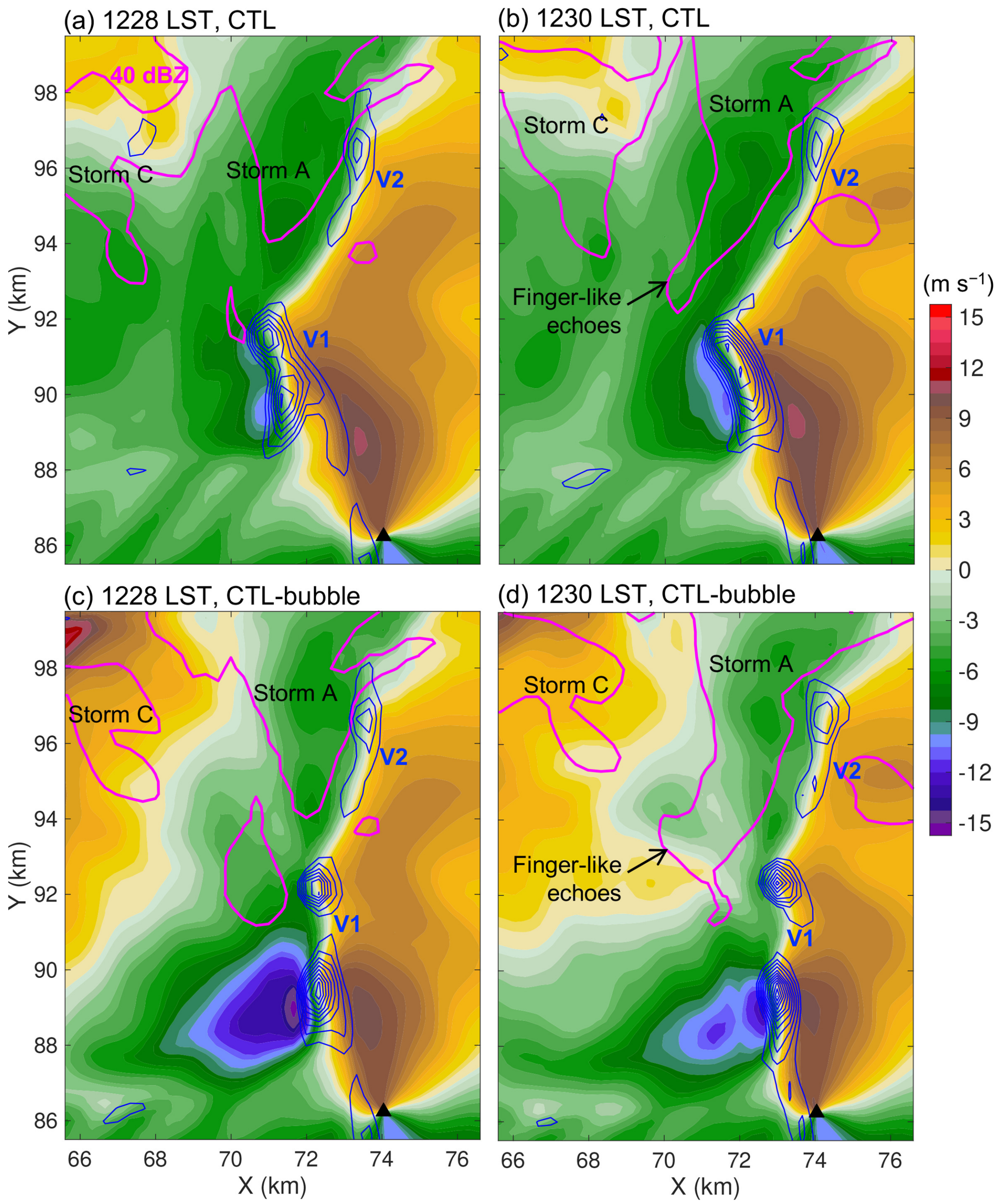

Fig. 10. Simulated radial velocities at the 8.1° elevation angle from the virtual X-PAR (black triangle) for the (top) CTL and (bottom) CTL-bubble experiments. The reflectivity is contoured at 40 dBZ in magenta. The vertical vorticity at model level 3 above ground is contoured in blue from 0.005 s^{-1} at an interval of 0.004 s^{-1}.

as indicated by the enhanced inbound radial velocity (refer to the dark blue shadings in Figs. 10c, d). Fueled by strong forced lifting when the cold outflow surges interacted with the southeasterlies from the PRD sea surface, the finger-like echoes subsequently wrapped up to be well-defined hook echoes (Fig. 11).

The results from the CTL-bubble sensitivity experiment support the hypothesis that an underestimation of low-level updrafts is a possible cause for the wrap-up failure of finger-like echoes in the CTL experiment. This sensitivity experiment also suggests that the stretching of ambient vertical vorticity over the triple point is sensitive to the cold outflow strength from preexisting storms. On the other hand, recalling the radar observations (inset of Fig. 8a), the cold outflow surges are not as strong as those in CTL-bubble experiment. This inconsistency may suggest that other equally important factors also contribute to the uncertainty of mesovortex formation on the finger-like echoes, such as the strengths of

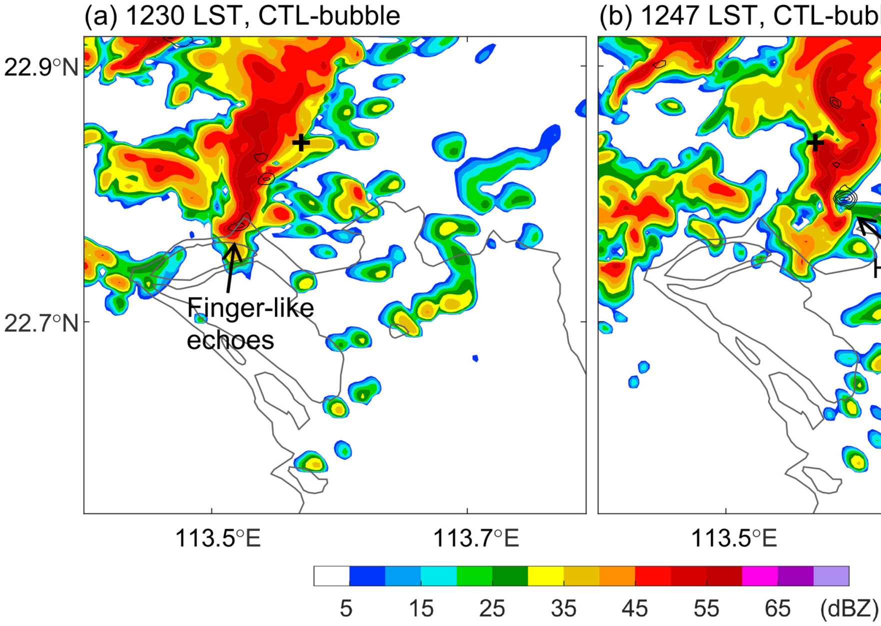

Fig. 11. Same as in Fig. 3 but for the CTL-bubble experiment.

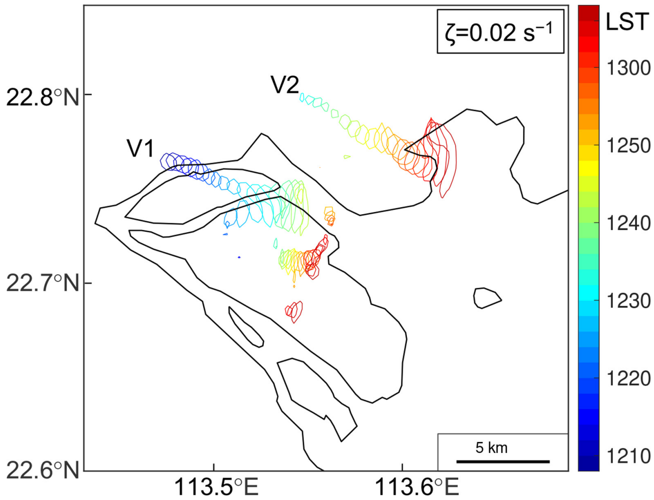

Fig. 12. Vertical vorticity isopleths of 0.02 s^{-1} (isopleths) on model level 3 above ground as calculated from the innermost domain of the CTL experiment on 1 June 2020. The colors represent different times on that day.

onshore flows and preexisting vertical vorticity. In the realistic scenario, the updrafts responsible for stretching the ambient vertical vorticity into a mesovortex were also likely provided by the forced lifting produced by the flow modification owing to the approaching storms that were merging with the observed finger-like echoes. In the simulated scenario, however, there was no merger between the finger-like echoes and any southern approaching storms.

4. Genesis of the simulated mesovortex in the CTL experiment

Although the finger-like echoes in the CTL experiment fail to wrap up and develop a mid-level mesovortex, two mesovortices are still reproduced in close proximity, both in time and space, to the realistic mesovortices (Part I). This suggests that a high predictability of mesovortex production can be expected in this environmental scenario, despite the fact that the specific genesis of a mesovortex is sensitive to storm-scale dynamics. This section investigates the possible mechanisms that lead to the relatively high predictability of mesovortex production with the aid of the CTL experiment.

The aforementioned three sensitivity experiments indicate that the probability of mesovortex genesis tends to be high as long as a storm moves through the preexisting triple-point ambient vortex (e.g., Vortex V1 in Fig. 9). However, a relatively long duration of collocation between such a storm and Vortex V1 is also required for the stretching process.

For instance, a storm labeled Storm B initiated to the south of Vortex V1 at 1237 LST and then propagated northeastward across Vortex V1 as shown in Fig. 9c. In the presence of preexisting enhanced ambient vertical vorticity, Storm B developed a well-defined hook echo signature. Nevertheless, it did not manage to develop a mesovortex because it quickly moved away and merged with Storm A. Meanwhile, the ambient Vortex V1 slowly moved toward the southeast (Fig. 12), in a different direction than Storm B, and thus leading to a relatively short overlapping time.

Although the finger-like echoes failed to wrap up, Storm A still subsequently developed a mesovortex with well-defined mesocyclonic signatures. Through an inspection of the simulated mesocyclonic signature and low-level vertical vorticity, the initial low-level vortex beneath the mid-level mesovortex was a locally enhanced ambient vortex along the boundary formed by the SE and COF flows (Vortex V2 in Fig. 9). As Storm A approached this boundary, its cold outflow further intensified the convergence and updrafts over Vortex V2 which continuously strengthened the vertical vorticity (Fig. 9). While Vortex V2 also moved in a different direction from the northeastward storm motion (Fig. 12), there was enough time for Vortex V2 to be stretched because the along-boundary length of convective area was relatively long (refer to the heavy black isopleths in Fig. 9). With nearby persistent low-level convective updrafts (Fig. 13a), Vortex V2 was subsequently stretched and finally developed into a mid-level mesovortex (Figs. 4a–c). By contrast, the stronger preexisting triple-point vortex (Vortex V1) failed to be stretched before 1310 LST due to

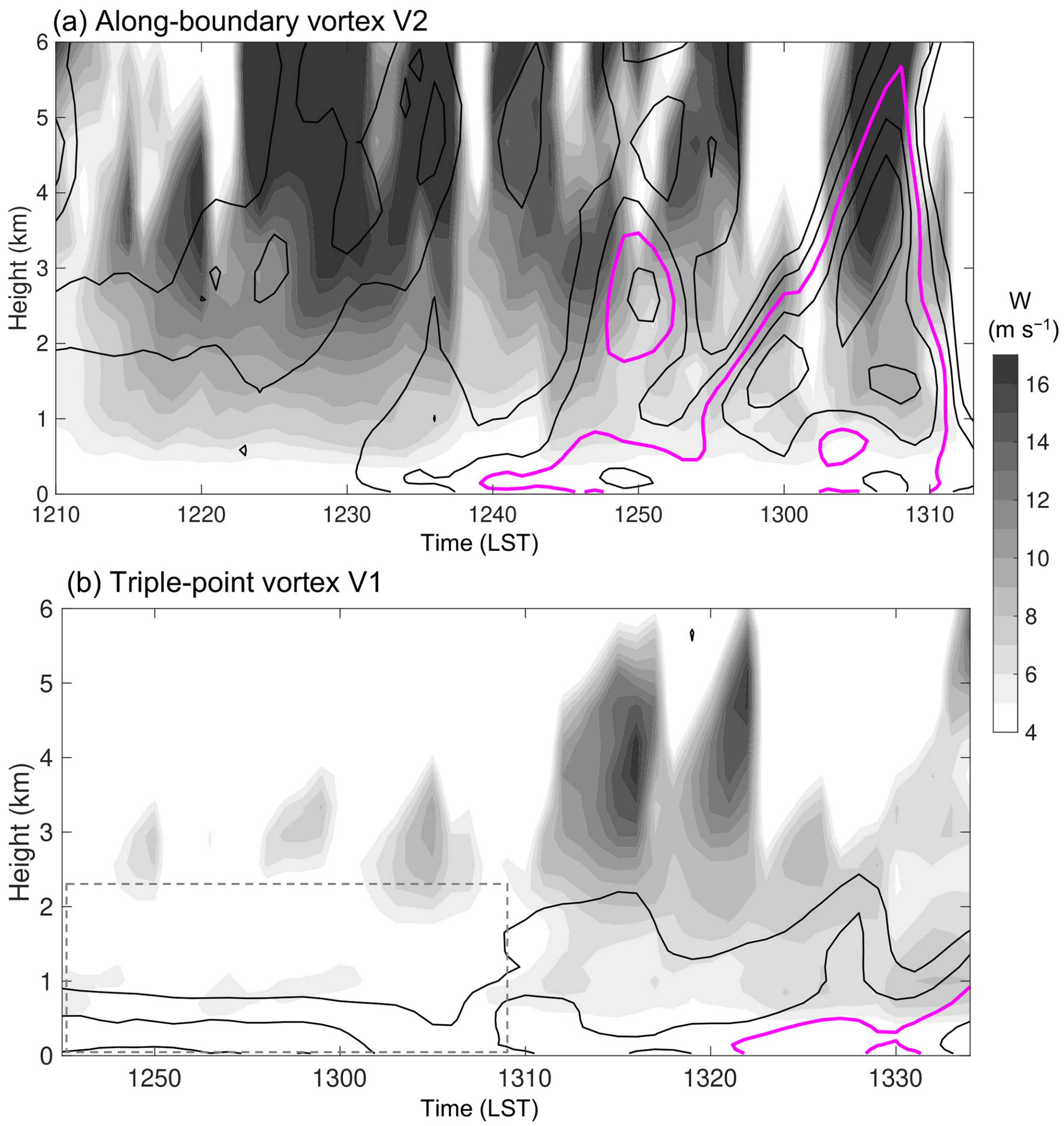

Fig. 13. Time–height diagrams of peak vertical vorticity (contoured from 0.015 s^{-1} at an interval of 0.005 s^{-1}; the 0.025 s^{-1} isopleth is highlighted in magenta) maximized on each level over the (a) along-boundary vortex V2 and (b) triple-point vortex V1 as shown in Fig. 9. The gray shadings represent the maximum vertical velocity within 2 km of the location of peak vertical vorticity. The dashed box in (b) is described in the text. All variables are calculated from the innermost domain of the CTL experiment on 1 June 2020.

the lack of low-level updrafts (refer to the dashed rectangle in Fig. 13b). As the western convection approached and thus intensified the upward motions at low levels, the triple-point vortex was gradually enhanced and stretched to form the mesovortex MV-2 (Hook echo B in Fig. 2f) as shown in Figs. 4d–f.

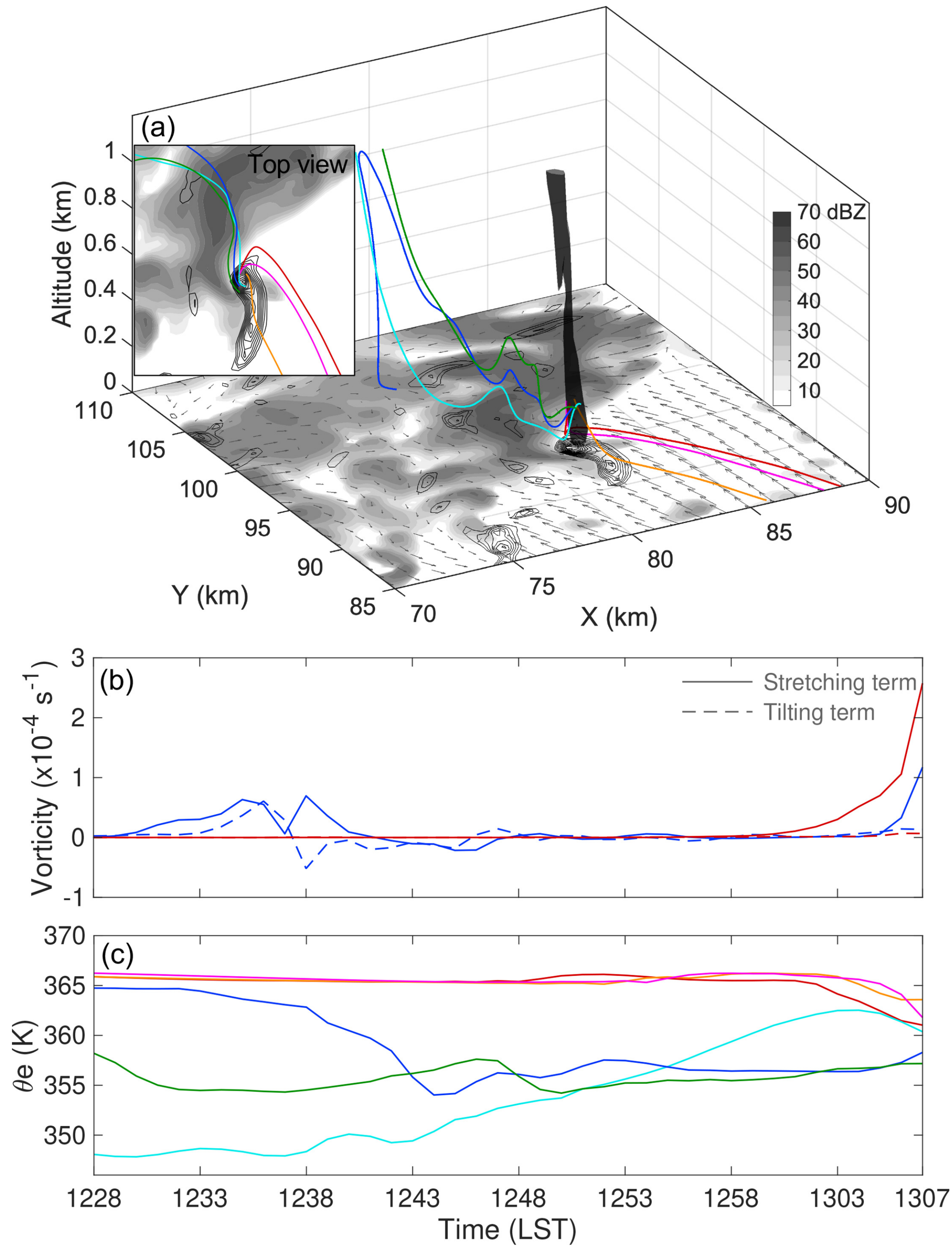

Fig. 14. (a) Three-dimensional isosurfaces (black column, 0.025 s^{-1}) of vertical vorticity at 1307 LST on 1 June 2020. The simulated reflectivity (shaded in gray), vertical vorticity (black isopleths, contoured from 0.005 s^{-1} at an interval of 0.004 s^{-1}), and horizontal winds (vectors) for model level 5 above ground are also shown at the bottom for reference. Several backward trajectories (terminated at a 200-m altitude) around the enhanced vortical vorticity are plotted by colored curves. A top view is also presented in the upper-left corner. (b) Vertical vorticity tendency for the air parcels marked by the red and blue lines in panel (a) with corresponding line colors. The stretching and tilting terms are represented by solid and dashed lines, respectively. (c) Equivalent potential temperature for the air parcels in panel (a) with corresponding line colors. All variables are calculated from the innermost domain of the CTL experiment on 1 June 2020.

Backward trajectory calculations terminating in the mesovortex at 200 m AGL (refer to the colored lines in Fig. 14a) confirm that the persistent low-level updrafts over Vortex V2 played a key role in the vortex intensification, as low-level stretching was the dominant vorticity-generation term (Fig. 14b). In this study, the backward trajectory calculation was conducted using the RIP (Read/Interpolate/Plot) software package, version 4, that invokes NCAR Graphics routines. Given the 1-min time interval of the WRF outputs, a time step of 10 s was set for trajectory calculations, and velocity data were linearly interpolated in time to the trajectory time steps. The time-integrated vertical vorticity generated through vertical stretching ($\zeta\partial w/\partial z$) and tilting ($\xi\partial w/\partial x+\eta\partial w/\partial y$) was calculated along the parcel trajectory. Here ξ, η, and ζ represent the components of the vorticity vector at the x, y and z directions, respectively. Figure 14a shows that the airmasses in the mesovortex originated from the descending air parcels from storms and near-ground ambient air parcels within the southeasterlies over the PRD sea surface. The low-level airmasses from the southeast had higher instability than those from the precipitation regions. Within onshore monsoonal flows, they were initially characterized by high equivalent potential temperature and subsequently underwent a rapid drop of approximately 4 K from the ground level to an altitude of 200 m during its mixing with the descending air parcels from storms (Fig. 14c).

Although the CTL experiment provides seemingly plausible results, in the context of a dynamic diagnosis, the above analysis suggests "the right results but for the wrong reason". The simulated Storm A seemingly reproduced finger-like echoes, a mid-level mesovortex, and supercell-like structures in the rain fields, but with a slightly different mechanism in regards to the detailed genesis process of a mesovortex. On the storm scale, the simulated finger-like echoes failed to wrap up due to the lack of persistent, strong enough upward motions at low levels near the triple point. The simulated mesovortex originated from the preexisting locally enhanced ambient vortex along the surface convergent boundary (Vortex V2). The persistent low-level updrafts along this boundary finally prompted the mesovortex formation and the supercell-like structure in the reflectivity field. Similar to the second observed mesovortex (Part I), another simulated mesovortex formed over the triple point zone owing to the arrivals of persistent low-level updrafts associated with the approaching widespread convection (Fig. 3f and Figs. 4d–f). The simulated Storm B also indicates that a displacement of the triple point and storms, due to diverging directions of propagation (Fig. 9c and Fig. 12), makes it difficult to intensify the preexisting ambient vertical vorticity for developing a mid-level mesovortex. Consequently, although the predictions of rotating storms are sensitive to environmental and storm-scale details at low levels, the simulated and observational facts suggest that there is a high probability for an upcoming storm to develop a mesovortex over the triple point that is associated with the land–sea contrast of a trumpet-shaped coastline.

5. Summary and discussion

This study is the second part of a two-part series study on the influence of irregular coastlines on a tornadic mesovortex in the Pearl River Delta during monsoon season. In the first part (Part I) of this case study, the prestorm environments on 1 June 2020 were investigated along with the roles of the triple point that was associated with the land–sea contrast of a trumpet-shaped coastline in the development of the tornadic storm. The analyses in Part I were conducted primarily based on a rapid-scan X-band phased array radar, an S-band operational radar, and in situ surface weather stations. The work presented in the current article (Part II) was designed to complement the observational analysis of the tornadic mesovortex with the aid of multiple sensitivity numerical simulations.

Twin simulations were conducted by using a realistic coastline (CTL experiment) and replacing the PRD sea surface with fake land (CTL-land experiment) to identify the roles played by the trumpet-shaped coastline in the formation of rotating storms in a low-shear environment containing intersecting airmass boundaries. The CTL experiment produced two mesovortices near the intersection zone (triple point) of three types of airmasses (i.e., preexisting storm-generated cold outflows, prevailing monsoonal southwesterlies on land, and southeasterlies over the PRD sea surface). Similar to the observed tornadic storm that developed on the triple point, a simulated mesovortex was produced by initially stretching the preexisting ambient vertical vorticity over the triple point. The other simulated mesovortex was produced approximately 6 km to the north of the triple point. It developed from a local maximum of vertical vorticity along the airmass boundary formed by preexisting storm-generated cold outflows and sheared onshore flows from the southeast. The preexisting enhanced ambient vertical vorticity developed more deeply through persistent upward motions along the airmass boundary and strengthened into a mid-level mesovortex. In the CTL-land experiment, no triple point was generated due to the absence of a trumpet-shaped coastline, thus a rotating storm was not produced. This pair of sensitivity simulations suggest that the unique land–sea contrast of the PRD is an essential component for the repeated occurrence of enhanced vertical vorticity during the summer monsoon season. The sheared onshore flows over the PRD surface also tend to slow down the eastward propagation of storms.

On the storm morphology, similar to the observed finger-like echoes, the CTL experiment reproduced well-defined finger-like echoes when the preexisting cold outflow surges intruded into the triple point zone. However, the simulated finger-like echoes were short-lived and did not manage to wrap up as the observed ones did. Another sensitivity experiment (CTL-bubble) was carried out to demonstrate that intensifying the forced lifting associated with the cold outflow surges has the effect of reproducing a mesovortex on the simulated finger-like echoes. In this experiment, the cold outflow surges were artificially strengthened by injecting a volume of cold air upstream of the finger-like echoes.

Fueled by stronger forced lifting, the simulated finger-like echoes successfully wrapped up with a mid-level mesovortex.

Results from the three sensitivity numerical simulations suggest that a high likelihood of rotating storms can be expected when preexisting storms juxtapose with the triple point associated with the land–sea contrast of trumpet-shaped coastline. For the short-term probability forecast by convection-permitting modeling, the "correct" result matters even if the detailed storm-scale processes are not perfectly the same after an in-depth, post-event investigation. Although the genesis processes of the simulated mesovortices are not completely consistent with the scenario suggested by multi-source observations, these simulations provide important guidance for assessing the rotating storms in this region. The discrete vortices transformed from the vortex sheet associated with the airmass boundary via shear instability play an important role in the relatively high predictability of mesovortex production (Markowski et al., 2014). The presence of multiple local maxima in vertical vorticity both over the triple point and along the airmass boundary increases the risk of rotating storms which may spawn tornadoes even in a dynamic condition with low vertical wind shear. Compared to the along-boundary preexisting ambient vortex, the triple-point vortex is believed to provide a greater likelihood for an upcoming storm to organize into a rotating storm because of the stronger vertical vorticity in that region. Such a likelihood would be even greater if the storm propagates in the same direction with the preexisting boundary. In this situation, the low-level convective updrafts tend to overlap with the triple-point vortex for a relatively long duration for stretching.

Tornado statistics have shown that the PRD is a tornado-prone region. Although it is still not clear exactly how many tornadoes were associated with such non-mesocyclone processes, the current study suggests that the topography-related localized ambient vertical vorticity that results from storm-boundary interaction is likely an important component for the formation of rotating storms in this region. It should be noted that this mechanism is conspicuous during the monsoon active season when the PRD region is characterized by prevailing southwesterlies in the lower troposphere. More in-depth case studies are warranted to better understand the prominent formation mechanisms of regional tornadic storms, which would greatly support the severe weather forecasting over this tornado hotspot.

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