Hailstorm Formation Enhanced by Meso-γ Vortices along a Low-Level Convergence Line

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(Received March 25, 2020; in final form August 13, 2020)

ABSTRACT

During a hailstorm event, near-surface meso-γ vortices along a convergence line interact with hail cells. Herein we investigate this interaction by using observational data and a high-resolution simulation of a hailstorm that occurred over Taizhou (Zhejiang, China) on 19 March 2014. The 10-m surface wind data from automatic weather stations show that several meso-γ vortices or vortex-like disturbances existed over the convergence zone and played a vital role in the evolution of the hailstorm and the location of the hail. The model results agree with the observations and present a closer correlation between the hail and the low-level meso-γ vortices than those observed. The model simulation indicates that such low-level meso-γ vortices can be used to predict the next 10-min hail fallout zone. The low-level meso-γ vortices originated over the convergence zone and then fed back into the convergence field and provoked a stronger updraft. Vorticity was initiated primarily by stretching and was extended by tilting. A three-dimensional (3-D) flow analysis shows that the existence of low-level meso-γ vortices could help enhance a local updraft. Furthermore, the simulation reveals that the low-level meso-γ vortices formed in the bounded weak echo region (WER) at the front of the hail cell, enhancing convergence and strengthening updrafts. Graupel was broadly located between the 0°C isothermal line and the top of the clouds, roughly between the 0 and –20°C isothermal lines. Accordingly, the hailstones grew rapidly. The suitable environment and the positive effect of the meso-γ vortices on the updrafts enabled hailstorm formation.

Key words: hailstorm, meso-γ vortices, special terrain, high-resolution simulation, strong updraft

Citation: Zhang, H. L., H. F. Shen, and G. Q. Zhai, 2020: Hailstorm formation enhanced by meso-γ vortices along a low-level convergence line. J. Meteor. Res., 34(6), 1271–1286, doi: 10.1007/s13351-020-0030-x.

1. Introduction

Hailstorms adversely affect agriculture and society. In the last few years, several studies have reported increasing incidents of hail damages and increasing hailstorm durations (e.g., Niall and Walsh, 2005; Zhang et al., 2008; Kunz et al., 2009; Botzen et al., 2010). Consequently, hailstorm studies have attracted increasing interest. Various advanced observational techniques and numerical weather prediction (NWP) models have been used to study hail (e.g., Witt and Nelson, 1991; Hong and Fan, 1999; Li et al., 2002; Fang et al., 2005; Donavon and Jungbluth, 2007; Zhang and Li, 2019). However, it is still difficult to observe and predict the evolution of a hailstorm at small spatial and temporal scales (Zhou et al., 2019; Zhang et al., 2020).

Hail is a significant deep convection phenomenon. Deep convection initiation and the organization of convective storms are highly relevant to boundary layer convergence lines (Wilson and Schreiber, 1986). Fankhauser et al. (1995) found that deep convection was initiated along a low-level convergence line because the vertical velocity maximum was located over the associated convergence zone. The interactions between different convergence zones (i.e., sea-breeze fronts, gust fronts, drylines, and cold fronts) create preferred locations for

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deep convection (e.g., Lee et al., 1991; Harrison et al., 2009; Sun and Fang, 2013). A low-level convergence zone with misocyclones (small-scale vertical vortices with diameters smaller than 4 km; Markowski and Richardson, 2010) or mesoscale vortices can enhance updrafts so as to induce deep convection (e.g., Wilson et al., 1992; Atkins et al., 2004, 2005; Buban et al., 2012; Xu et al., 2015; Zhai et al., 2015). Several studies have demonstrated that strong updrafts are common at the initial stage of hail formation (e.g., Browning and Foote, 1976; Heymsfield et al., 1980; Kennedy et al., 2014). Nelson (1983) used multiple-Doppler data and a numerical hail model to analyze the influence of the storm flow structure on hail growth. He found that the storm updrafts were sufficiently strong to lift embryos before full-scale hailstorm occurred. Knight and Knight (2001) demonstrated that strong updrafts played an important role in sustaining large hail. In addition, cold fronts have been associated with significant updrafts that could enable the occurrence of hailstorm through convergence and wind shear (e.g., Locatelli et al., 2002; Schemm et al., 2016).

Pulse-type storms refer to weakly forced storms associated with severe weather (Miller and Mote, 2017). These storms are generally not tornado producers but often produce large hail and/or damaging winds. Such storms are generally characterized by slow movement, weak flow and shear environments, and an elevated core of high reflectivity; short lived, typically lasting from 30 min to 2 h; appearing randomly; and not triggered by any organized dynamic feature (Cerniglía and Snyder, 2002). Pulse-type storms, especially pulse-type hailstorms, are often difficult to provide warnings for. Numerous NWP models have been specifically designed for predicting and simulating hailstorms. Even though these models have several disadvantages, they are currently the best tools available for analyzing the structure of hail cells, hail formation, and hail growth mechanisms (e.g., Orville, 1977; Farley, 1987; Speer et al., 2004; García-Ortega et al., 2007). Orville and Kopp (1977) used a two-dimensional cloud model to simulate the evolution of hail cells and hailstorms; they revealed the structure of hail cells and the life history of a hailstorm. Guo and Huang (2002) used a three-dimensional (3-D) cloud model with hail-bin microphysics to successfully simulate a multicellular hailstorm and found that the formation of a feeder cell with a weaker updraft along the side of a main cell was important for the evolution of a hailstorm. Chevuturi et al. (2014) used the Weather Research and Forecasting (WRF) model to study a winter hailstorm event and found that deep instability in the atmospheric column led to hailstorm formation.

In this study, we focus on a pulse-type hailstorm (Luo et al., 2017) that occurred in Taizhou (Zhejiang, China) during 0700–1000 UTC 19 March 2014. In addition, we identify a series of low-level meso-γ vortices along the low-level convergence lines. The horizontal dimension of this type of a low-level vortex, for a vertical vorticity magnitude of over $1 \times 10^{-4}$ s$^{-1}$, varies from 1 to 20 km. These low-level vertical vortices are similar to misocyclones but differ in their horizontal scales. Therefore, we defined them as meso-γ vortices (Orlanski, 1975). This study aims to demonstrate the existence of meso-γ vortices along convergence lines and to investigate the relationship between these meso-γ vortices and the hail location based on the output of a high-resolution model. Furthermore, the influence of meso-γ vortices on hail cells (e.g., the updraft) is examined.

The rest of this paper is organized as follows. Section 2 presents an introduction of the hailstorm event, including the damages, a synoptic background, and surface observations. The design of the model experiment and a detailed comparison of the model results and the observational data are presented in Section 3. An analysis of the relationship between the meso-γ vortices and the hail based on the numerical simulation is presented in Section 4, and conclusions are drawn in Section 5.

2. Case description

2.1 Case overview

Severe convective weather phenomena occurred in most parts of Zhejiang Province on 19 March 2014. Thunderstorms covered nearly the entire province, and the average 1-h accumulated rainfall during this event was approximately 10–20 mm. This severe convective system moved southeastward, and a hailstorm hit southeast Zhejiang Province (i.e., Taizhou and Wenzhou). Damage from this hailstorm, which was one of the greatest in Taizhou City history, was estimated at around 70 million Chinese Yuan. According to the observational data from Taizhou Weather Bureau, on the afternoon of 19 March 2014, thunderstorms and severe winds formed and rapidly moved southeastward between 0810 [1610 local standard time (LST)] and 1020 UTC (1820 LST). During the movement of this severe convection, gust wind at levels of 10–12 on the Beaufort scale and large surface hail were recorded at several automatic meteorological stations (mesonets) in Taizhou City. The maximum diameter of the hailstones was 3.3 cm, which was observed at the Hongjia synoptic station (Huang and Gao, 2016). This event was mainly caused by a cold front. Taizhou City was situated in front of the cold front and un-
under the influence of a warm temperature ridge, which brought warm and wet air (Luo et al., 2017).

2.2 Surface feature evolution

Surface data from 0740 to 0850 UTC obtained from conventional and automatic weather station data were provided by the Hangzhou Weather Bureau. The locations of the stations are presented in Fig. 1. A Cressman objective analysis was used to interpolate the station data into the grid data (Gilchrist and Cressman, 1954).

In Fig. 2, the yellow-shaded region indicates the terrain height information, which reveals the main geomorphological features of Taizhou City. These data show that the combination of a cold front and a surface convergence line was the dominant factor of this hailstorm. Taizhou City extends northeast–southwest along a valley, which coincides with the convergence line (the southern red dashed line in Fig. 2a). A meso-γ vortex (the red arrow in Fig. 2a, with a horizontal scale of approximately 20–30 km) existed at the southern end of the convergence line. The southern convergence line and the meso-γvortex remained essentially unchanged for about 1 h (from 0640 to 0740 UTC; figure omitted). This convergence line and the meso-γ vortex formed because of the distinctive terrain in the area. The southeast airflow was blocked by the terrain and formed a convergence line along the foothill. This distinctive terrain forced a meso-γ vortex to form at the bottom of the valley. Studies (e.g., Levinson and Banta, 1995; Aebischer and Schär, 1998) have demonstrated that terrain-forced vortices can be found in foothill areas and that topographic effects could provide a low-level source of vorticity. The cold front (the northern red dashed line in Fig. 2a) with convergence centers with vorticity of $-1 \times 10^{-4}$ s$^{-1}$ (blue thin dashed lines in Fig. 2b) existed between the rainfall region (color shaded region in Fig. 2a) and the northern foot of the Tiantai Mountain (marked TTM in Fig. 2).

Twenty minutes later (Figs. 2c, d), the cold front and the rain belt were located over the TTM, and the cold air provided by the northwesterly flow started to come into contact with the southern convergence line. Then, the convergence increased significantly, reaching a maximum vorticity of $-2 \times 10^{-4}$ s$^{-1}$. At that time, the intensity of the meso-γ vortex increased, and a vorticity center of $1 \times 10^{-4}$ s$^{-1}$ (green-shaded in Fig. 2d) was established near the convergence center, which indicated a vortex distribution in the surface wind field. The 10-min accumulated precipitation over the next 10 minutes also experienced a significant increase, and a precipitation center appeared with a value of over 10 mm. In addition, a hailstorm occurred near the meso-γ vortex at 0800 UTC (red triangles in Fig. 2c). Figure 2e shows the surface wind at 0820 UTC and the 10-min accumulated precipitation between 0820 and 0830 UTC. At that time, the southern convergence line completely merged with the cold front (which was ahead of the rain belt), crossed the TTM, and caused a series of hailstorms in the valley along the convergence line. The wind convergence increased further, and the meso-γ vortex temporarily disappeared. After 30 min, the cold front moved to Linhai (marked LH in Fig. 2). An anticyclonic-vortex center, which was associated with a vorticity center of $-1 \times 10^{-4}$ s$^{-1}$, emerged at the convergence center. According to the disaster report made by the Taizhou Weather Bureau, a severe convective storm outburst was reported at 0850 UTC in LH. This phenomenon might indicate that the meso-γ vortices (including cyclonic and anticyclonic) could help enhance the near-surface convergence. The maximum hail diameter at the Hongjia weather station was 25 mm, which fell on the ground 10 min (0900 UTC) after the anticyclonic and cyclonic vortex distribution formation. From the evolution of the surface wind field and the development of the severe storms, it appeared that the interaction between the cold air ahead of the cold front and the convergence line located along the foot of the TTM strengthened the severe convective storm. Moreover, the vortex distribution along the convergence line enhanced the convective storm development and somewhat reflec-

![Fig. 1. Locations of the conventional and automatic weather stations (gray points). The red symbol denotes the location of Hongjia sounding. The green star indicates the location of Taizhou radar. The yellow colormap indicates topography height (m). District names are abbreviations as follows: Tiantai (TT), Sanmen (SM), Xianju (XJ), Huangyan (HY), Jiaojing (JJ), Wenling (WL), Jinyun (JY), Yiwu (YW), Linhai (LH), Qingtian (QT), Yueqing (YQ), and Yuhuan (YH). TTM denotes the location of the Tiantai Mountain. The rectangular box in the figure indicates the area covered by Fig. 3.](image-url)
Fig. 2. Surface element field. (a, c, e, g) Surface wind vector (m s$^{-1}$), 10-min accumulative rainfall (mm; rainbow colormap), and terrain elevations (m; yellow colormap); (b, d, f, h) surface wind vector (m s$^{-1}$), surface vorticity field ($\times 10^{-4}$ s$^{-1}$; green colormap), surface convergence field ($\times 10^{-4}$ s$^{-1}$; divergence every $1 \times 10^{-4}$ s$^{-1}$; thin blue dashed line starting at $-1 \times 10^{-4}$ s$^{-1}$), and terrain elevations (m; yellow colormap). (a, b) 0740 UTC, (c, d) 0800 UTC, (e, f) 0820 UTC, and (g, h) 0850 UTC. District names are abbreviated as follows: Tiantai (TT), Linhai (LH), Sanmen (SM), Xianju (XJ), Huangyan (HY), Jiaojiang (JJ), Wenling (WL), Dongyang (DY), Jinyun (JY), and Yongjia (YJ). TTM denotes the location of the Tiantai Mountain. The red triangles denote the location of hail fallout areas. The red arrow denotes the meso-$\gamma$ vortex. The red dashed line in (a) and (c) denotes the convergence line. The rectangular box in the figure indicates the area covered by Fig. 3.
ted the hail fallout zone.

With regard to the local geomorphology, TT also lies in a valley; therefore, we zoomed in on the TT region to check if the valley had the similar phenomenon. Figure 3 shows the evolution of the wind field and the severe storm in the TT region (the black box in Figs. 1 and 2a) at 0740–0810 UTC. To present mesoscale information in more detail, the Shuman–Shapiro filter (e.g., Shuman, 1957; Shapiro, 1970; Wang et al., 2007) was used to process the station data. As shown in Fig. 3, there is a meso-γ vortex in this region (marked “C”), and a convergence line existed along the TTM. At 0710 UTC (Fig. 3a), a meso-γ vortex circulation (“C”, with horizontal scale of about 10 km) was located at the bottom of the valley. At that time, “C” had not formed a closed vortex, and was still a vortex circulation. This vortex should also be a terrain-forced vortex. A half hour later (0740 UTC; Fig. 3b), the convergence line was still along the TTM with the convergence increased. The vortex “C” formed and was combined with a convergence center. After 20 min, a hailstorm occurred at the position of the vortex “C.” Then, “C” disappeared. After 30 min, a strong reflectivity center (over 60 dBZ) was observed at the vortex region. The reflectivity at the meso-γ vortex place was stronger than that at others. Reflectivity data were obtained from Taizhou station. The radar antenna wavelength is 10 cm. The beam width is 0.99°. The pulse repetition frequency (PRF) is between 322 and 1282 Hz. We plotted the cross-section (Fig. 4b) along A–B (Fig. 4a). The meso-γ vortex was located to the east of the strong echo column, and a strong reflectivity center was located over the meso-γ vortex. The strong echo column was tilted to the top. A weak echo region (WER) existed at the vortex region.

3. Model configuration and verification

In this section, we introduce the model configuration and verify the model results using the observational data from the conventional and automatic weather stations, the sounding data from the Hongjia observation station, and the disaster report from the Taizhou Weather Bureau.

3.1 Model configuration

The advanced research version of the WRF model (ARW; Skamarock et al., 2005; Klemp et al., 2007) was used to reproduce this case. The numerical experiment was performed by using WRF v3.7.1 with four domains and two-way nesting (Fig. 5). The model domains consisted of a 27-km grid with a mesh size of 274 × 203, a 9-km grid with a mesh size of 448 × 319, a 3-km grid with a mesh size of 580 × 421, and a 1-km grid with a mesh size of 400 × 400. The vertical level was 45, and 12 levels were configured below 2 km. The time step was 90 s in Domain 1 with a time step ratio of 1 : 3 : 3 : 3. All four domains were integrated for 24 h from 1200 UTC 18 to 1200 UTC 19 March 2014. The initial and outermost lateral boundary conditions were provided by the 1° resolution Final Operational Global Analysis data (FNL; https://rda.ucar.edu/datasets/ds083.2/) at 6-h intervals. The following model physical schemes were used: (1) the Milbrandt–Yau two-moment microphysics scheme (Milbrandt and Yau, 2005a, b), which is a multimoment
3.2 Model verification

3.2.1 Rainfall

A comparison of the simulated and observed 1-h accumulated precipitation shows that the WRF model reproduces the evolution of the precipitation systems well. Though this cold-front event process did not produce sufficient precipitation, the evolution of the precipitation systems likely reflected the evolution of the cold front well. Figure 6 indicates that the rain belt moved from northwestern to southeastern Zhejiang Province. Results showed that the simulated precipitation (shaded in Fig. 6) was larger than the observed precipitation (contour in Fig. 6), especially in the western section of the rain belt. Therefore, despite the overprediction of precipitation, the model exhibited good skill in predicting the movement of the rain belt.
belt and the cold-front process. In addition, focusing on the period when the hailstorm occurred in Taizhou (shown in Fig. 6d), an obvious increase in the 1-h accumulated precipitation was noted in both the simulation and the observational data. The location and intensity of the precipitation center in the coastal areas of the Zhejiang Province are similar in the simulation and observations. Moreover, during the hailstorm period (0800 UTC), simulated rainfall center and strength in the coastal areas in Zhejiang Province demonstrated a great similarity to the observed. To study the hailstorm, we considered that it could be used as the key period and area for further analysis. Therefore, in terms of the evolution of the simulated 1-h accumulated precipitation, the WRF model-simulated path and movement speed of the rain belt are in good agreement with the observational data, particularly for the Taizhou City.

3.2.2 Hail

Figure 7 compares the simulated hail fallout zone to the observed hail fallout zone. The observed hail fallout zone was derived from the disaster report drawn by the Taizhou Weather Bureau. The simulated hail precipitation amounts [also used by Chevuturi et al. (2014)] were from 0750 to 0900 UTC for the model-simulated domain at a 1-km horizontal resolution. As shown in Fig. 7, the model simulation generally agreed with the observations. For instance, the WRF model reproduced the main hail fallout zones in TT, XJ, and LH well. In addition, the two directions of hailstorm propagation (the red arrows in Fig. 7) were simulated well. Although the hail fallout zone at the south of XJ was not simulated by the WRF model, the model still demonstrated a good ability to simulate this hailstorm when the main hail fallout zone is considered.

3.2.3 Sounding

To demonstrate the capacity of the model to reproduce the atmospheric fields in the regional scale environment, we compared the model and observed sounding data of Hongjia station (available at http://weather.uwyo.edu/upperair/sounding.html), which is the only sounding station in Taizhou City on 19 March 2014. The simulated and observed sounding at 0000 UTC (Fig. 8a) before the hailstorm occurred showed that the model reproduced the observed profiles of the temperature and horizontal winds on the morning of 19 March 2014 reasonably well. However, there were some differences between the simulated and the observed moisture profiles in the middle troposphere. There was a strong wind shear at low levels and an inversion layer below 850 hPa.

Although the simulated and observed moisture profiles
had similar trends (i.e., the same trend below 850 hPa, a relatively dry layer between 400 and 850 hPa, and a slight increasing trend over 400 hPa), the simulated moisture in the 400–850-hPa region was higher than that observed. This may be caused by an overestimation of the middle tropospheric southwesterly wind speed, which always contains plenty of water vapor. Furthermore, both the simulation and observation had a warm low-level advection, which helped increase the low-level moisture and instability. Several studies have shown that dry level over a warm moist layer close to the ground is favorable for the occurrence of hailstorm (e.g., Craven et al., 2002; Yu and Zheng, 2020). Therefore, the environment was suitable for a hailstorm to occur. In addition, the observed wind at 700 hPa was stronger than the simulated wind. This error was likely caused by the insufficient information in the initial and boundary conditions in the model, particularly the mesoscale information. The observed wind at 700 hPa increased quickly with height. Therefore, this strong wind at 700 hPa could help form a strong turbulence and instability. The model could not capture this rapid increase in the wind at 700 hPa. However, the model also had a vertical wind shear; the 600-hPa wind speed demonstrated an obvious increase; and the middle troposphere had more moisture than observation. Therefore, convection could be triggered. After the hailstorm (1200 UTC 19 March 2014; Fig. 8b), the simulation also reproduced the temperature and horizontal wind well. Furthermore, the moisture profile was also reproduced reasonably well.

In summary, despite the presence of some deficiencies in the detailed features, the abovementioned results imply that this simulation reproduces the evolution of the rain belt, the hail fallout zone, and the region environment reasonably well. Based on the general agreement between the simulation and the observations, we can use this model output in a further analysis.

Fig. 7. Comparison between the simulated (mm; shaded) and observed (triangle) hail fallout zones. The red arrows indicate the direction of propagation. The yellow colormap indicates topography height (m).

Fig. 8. Comparison between the simulated (black) and observed (red) sounding taken at Hongjia station. (a) 0000 UTC and (b) 1200 UTC. The location of Hongjia station is shown in Fig. 1.
4. Characteristics of meso-γ vortices along the convergence line

4.1 Evolution of the meso-γ vortices

To examine the influence of the local geomorphology in Taizhou City, we chose $\sigma = 0.954$ (a height of about 400–500 m) as a representative level for near-surface horizontal flow. Results show that the vortices are in good correspondence with the next 10-minute hail fallout zone. Figure 9 shows the streamline and the convergence during the next 10-minute accumulated hail precipitation at TT (the northern part of the Taizhou City). The next 10-minute hail fallout zone moved as the meso-γ vortices shifted along the convergence line. At 0720 UTC (Fig. 9a), there was a persistent southwesterly flow existing at the south of the TT region. A convergence line (the red dashed line) was located at the north of the TT region. Besides, there had just been a flow confluence at the generation location of vortex “V1” (the red circle in Fig. 9a). Vortex “V1” first occurred at the west of Longxi at 0730 UTC (Fig. 9b). The convergence line (the red dashed line) at that time was still located at the north of the TT region. The simulated vortex and convergence line pattern are similar to those of the observed result (Fig. 3a). At 0740 UTC, the convergence line moved southward and merged with the meso-γ vortex. The convergence strength at the west of Longxi increased. “V1” was still stabilized at the west of Longxi (Fig. 9c), which was also at the bottom of valley and similar to observed meso-γ vortex, and was accompanied by a convergence center. The next 10-minute accumulated hail precipitation amount showed that the hail fallout zone was strongly correlated with “V1.” With the movement of the convective systems, the convergence also continued to shift southeastward. At 0750 UTC, “V1” moved to Longxi (Fig. 9d) and was accompanied by a convergence increase. In addition, it was followed by the next 10-minute hail precipitation amount center. Then, “V1” started to fade, and another vortex “V2” formed at its eastern strong convergence zone at 0800 UTC (Fig. 9e). The vorticity intensity of “V2” exceeded $1 \times 10^{-3}$ s$^{-1}$. The hail fallout zone at the next 10 minutes of 0800 UTC showed that the second hail precipitation amount center was located at the location of “V2.” Subsequently, “V2” moved northeastward, in accordance with the northeastward movement of the hail fallout zone (figure not shown).

To better examine the evolution of the near-surface vortices, we chose the “V1” vortex as a representative sample. The time–height series of “V1” (Fig. 10) described the average of 9-point (3 km × 3 km) center of the vortex (we defined the vortex center according to the streamline at $\sigma = 0.954$). Figure 10a shows the change of vorticity and divergence at the initial region. The above analysis showed that “V1” initially formed at 0730 UTC. The result suggested that positive vorticity existed before convergence. Although there was no obvious vortex existing in the streamline field, the positive vorticity already existed. At 0640 UTC, there was no storm occurring near the TT region. The positive vorticity center existed at 0700–0710 UTC. After the occurrence of the positive vorticity center, a convergence center was generated. Figure 10b shows the elements at the vortex center, which indicates the evolution of vortex. At the onset stage of the vortex, positive vorticity originated at the near surface, which indicated that the near-surface vortex was derived from the near-surface flow. Gradually, the positive vorticity center extended upward, and negative vorticity appeared after 0800 UTC. As shown in Fig. 9, “V1” started to fade at 0810 UTC at the level of $\sigma = 0.954$ (the third level), which is mutual agreement with this time–height plot. The convergence field shows that the vortex formed in the convergence zone. After “V1” appeared, the convergence increased significantly, and the maximum convergence reached $-3.6 \times 10^{-3}$ s$^{-1}$. During the “V1” fading period, the convergence decreased. Obviously, the relationship between the vorticity and the divergence field reflected a feedback mechanism between vorticity and convergence.

To further examine the physical processes responsible for the development of the vortex, the budget of vertical vorticity is a favored approach (e.g., Zhang, 1992; Knievel and Johnson, 2003; Wang et al., 2016). The vertical vorticity equation can be written as follows:

$$\frac{\partial \zeta}{\partial t} = -\left( u \frac{\partial \zeta}{\partial x} + v \frac{\partial \zeta}{\partial y} \right) - \left( w \frac{\partial \zeta}{\partial z} \right) - \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + \left( \frac{\partial w}{\partial x} \frac{\partial u}{\partial z} - \frac{\partial w}{\partial y} \frac{\partial u}{\partial z} \right),$$

(1)

where $u$, $v$, and $w$ are the wind components, and $\zeta$ is the vertical vorticity ($\zeta = \partial v/\partial x - \partial u/\partial y$). The terms on the right-hand side of Eq. (1) represent vorticity changes due to horizontal advection, vertical advection, stretching, and tilting, respectively. The left-hand side of Eq. (1) indicates the change in the vertical vorticity. Based on the foregoing analysis, “V1” originated along the convergence line; therefore, the vertical stretching of the vorticity on “V1” must have played an important role in its genesis. Moreover, the conjunction of the outflow of the severe convective storm and the topographic convergence line may have acted to tilt the vortex line so that the tilting generation of the vorticity was also important.
Vorticity budget analysis illustrated that the vertical vorticity tilting and stretching are significant factors for the generation of meso-γ vortices (e.g., Trier et al., 1997; Kosiba et al., 2013; Markowski and Richardson, 2017).

The results of the vorticity budget (Fig. 11) also show that the stretching (Fig. 11c) and tilting (Fig. 11d) terms were more important than the others (Figs. 11a, b), particularly at low levels. The accuracy of the vorticity...
Fig. 10. Time–height plots. Vorticity ($\times 10^{-4}$ s$^{-1}$; shaded) and divergence ($\times 10^{-4}$ s$^{-1}$; contour) (a) at the vortex initial region, and (b) of the meso-$\gamma$ vortex.

budget was examined by comparing the value of the sum of the terms on the right-hand side of Eq. (1) (Fig. 11e) and the tendency of local relative vorticity (Fig. 11f). These two factors were similar. The residual of the local relative vorticity and the sum of the terms on the right-hand side (Fig. 11g) suggest that the residual term exhibited two weak positive centers at 0750 and 0800 UTC. The residual term is complex; it includes the numerical error, frictional effect term, and so on. Xu et al. (2015) treated the residual term as the frictional effect term. They found that the surface drag was important for meso-vortex genesis. In this case, the center at 0750 UTC probably contained the frictional effect. It was more likely that the other center was the numerical error. As the position of this center was high, the effect of surface drag should be very weak. It was also reasonable that the numerical error increased with the increasing calculation time. However, the residual term was small compared with the stretching and tilting terms. Therefore, it was not given considerable attention. The analysis of the vorticity budget also indicated that the stretching and tilting effects were dominant in our case (compared to the contributions of the horizontal advection and vertical advection). At the onset stage (0730 UTC), stretching was a major factor in the generation of the low-level vortex, whereas tilting had a weak negative effect. “V1” formed in a convergence region, and the depth of the convergence region was over 2 km; therefore, it was possible that stretching played an important role at the onset stage of the meso-$\gamma$ vortex. However, the skew-$T$ plot (Fig. 8a) indicates that the near surface wind and vertical wind shear were very weak and that low-level updraft near the surface (Fig. 12a) was small. These factors indicated that tilting was not important at the onset stage. During the development stage of the vortex, stretching maintained a positive contribution to the vortex. The positive stretching center had good correspondence with the low-level positive vorticity center; this indicated that stretching was a key factor in the life span of this vortex. The positive contribution of the tilting effect mostly occurred at the stage of positive vorticity development upward (after 0750 UTC), when the updraft increased obviously. This indicated that the storm might help tilt the vortex line and help the vortex develop upward. In addition, at a relatively high level (above the 0.74 km), both the stretching term and the tilting term provided a positive contribution to help develop positive vorticity.

4.2 Influence of the meso-$\gamma$ vortices on hail

4.2.1 3-D flow analysis of the meso-$\gamma$ vortices

The evolution of the 3-D flow was shown in Fig. 12, and we used this to indicate the variations of $u$, $v$, and $w$. The display region of this 3-D flow was depicted by the black box in Fig. 9b. Figure 12a shows the 3-D flow, which was at the center of vortex “V1” in TT at 0730 UTC. According to the horizontal streamline analysis at that time (Fig. 9), “V1” was at the bottom of the valley and had not merged with the convergence line caused by the severe convective system. As shown in Fig. 12a, there was an obvious turbulence near the surface; however, the intensity of updraft was not strong. After 10 min, there was a significant updraft of all the parcels at the center of “V1,” which indicated that the existence of the low-level vortex enhanced the local updraft. At that time, “V1” and the northern convergence line merged, and the vorticity of “V1” increased. The 3-D flow indicated that these parcels were initiated by over mountain flows and the outflow from the storm along the near-surface convergence line. The low-level vortex then formed more completely. At 0750 UTC (Fig. 12b), the flow ro-
tated and ascended simultaneously. The updraft showed a pronounced enhancement. In the meantime, followed by hail-shooting, there was a downdraft zone at the hail-shooting zone (the red-shaded region).

4.2.2 Vertical structure

To analyze the vertical structure of “V1” and the relevant convective cell, we plotted the cross-section along M–N (Fig. 9c). As shown in Fig. 13a, the near-surface meso-γ vortex “V1” was located near the strong echo wall, the near-surface flows (the cold outflow from the convective system and the warm easterly flow) converged over “V1,” and a strong updraft was tilted to the convective system reaching its top. A WER existed in association with “V1.” According to the abovementioned analysis, the existence of “V1” may help enhance the updraft. The maximum reflectivity to the west of the WER

Fig. 11. Time–height plots of the terms in the vorticity budget Eq. (1). (a) Horizontal advection term, (b) vertical advection term, (c) stretching term, (d) tilting term, (e) the sum of terms on the right-hand side of Eq. (1), (f) change of vertical vorticity, and (g) the residual term ($\times 10^{-6}$ s$^{-2}$; shaded).
exceeded 50 dBZ and extended to the ground. Another strong echo center of 42 dBZ appeared aloft between 6- and 12-km altitude and extended to the overhang. The overhang was prominent, and a roll circulation occurred in the overhang region, allowing the external airflow to be well mixed with the airflow in the convective system. The divergence field along the cross-section (Fig. 13b) shows an obvious convergence region over “V1”; the maximum convergence exceeded $-2 \times 10^{-3} \text{ s}^{-1}$. Moreover, a divergence region was observed at the top of the convective system. This pattern of low-level convergence and upper-level divergence could help to promote the development of the storm system. The potential temperature cross-section (Fig. 13c) showed that “V1” was located in the high potential temperature region, which contained high levels of unstable energy. This high potential temperature region corresponded to the strong convergence region and the strong echo region. In addition, the heights of 0 and −20°C isothermal lines were appropriate for hail. Under the promotion of powerful updraft, graupel was found to be broadly and horizontally widespread between the 0°C isothermal line and the top of the convective cloud. The hail-mixing ratio was mainly located in the strong updraft region in front of the strong echo column. This strong updraft contributed to maintenance of the growth of the hailstones.

5. Conclusions

Observational data from the mesonet and high-resolution outputs from a WRF model were used to study a hailstorm that occurred on 19 March 2014 in Taizhou City, Zhejiang Province, China. In particular, the mesonet data were used to examine the evolution of the surface flow and the time series of the surface pressure and wind. The WRF model was used to reproduce this case to decipher the genesis of the hail and the impact of the low-level meso-$\gamma$ vortices.

A series of low-level meso-$\gamma$ vortices was observed by mesonets in China. These low-level meso-$\gamma$ vortices formed along the near-surface convergence line and showed a strong correlation with the location of severe convective weather (i.e., torrential rainfall and hail). The streamline field suggests the formation of positive and negative vorticity centers, which could be associated with the maximum convergence centers. The 10-min accumulated precipitation was closely related to the convergence and vorticity centers. Accordingly, a high-resolution simulation using the WRF model was performed.

The model near-surface wind field clearly showed that several meso-$\gamma$ vortices existed along the convergence line and exhibited good correlation with the hail fallout zone. The simulated streamline field showed that hail occurred 10 min after the occurrence of the meso-$\gamma$ vortices. The evolution of the vorticity and divergence of the center of the meso-$\gamma$ vortices showed that the meso-$\gamma$ vortices formed in a low-level strong convergence region. The presence of the meso-$\gamma$ vortices enhanced the low-level convergence. The analysis of the vorticity budget indicated that the stretching vorticity generation mainly affected vortex generation at the onset stage, whereas the generation of tilting vorticity occurred with the upward development of positive vorticity. At the onset stage, the increase of the vorticity was nearly entirely caused by stretching, because the southwesterly flow experienced confluence due to the terrain; after the vortex formed, the existence of the meso-$\gamma$ vortex could help enhance the low-level convergence and updraft so that the stretching contribution remained large and the tilting contribution increased.

The low-level meso-$\gamma$ vortices formed along the convergence line could help strengthen the low-level convergence, which promoted the ascending motion and the de-
development of severe convective cloud. The strong echo column corresponded with the high-\(\theta_v\) region. High convective energy was beneficial to the convective cloud. The vortex located ahead of the strong echo column below the WER could enhance the near-surface convergence and updraft flow. Moreover, graupel was found broadly and horizontally widespread between the 0°C isotherms and the top of the convective clouds. The impact of the strong ascending motion contributed to the development of rich hailstones. The 3-D flow analysis indicated that vortex was formed by the environmental wind (i.e., over mountain flow and southerly flow) and the outflow from the storm cloud, and the existence of the meso-\(\gamma\) vortex could help in enhancing the updraft.

**Acknowledgment.** The authors thank Hangzhou, Taizhou, and Wenzhou Weather Bureau for providing observational data. The authors would like to thank Enago (www.enago.cn) for the English language review.

**REFERENCES**

Aebischer, U., and C. Schär, 1998: Low-level potential vorticity and cyclogenesis to the lee of the Alps. *J. Atmos. Sci.*, **55**, 186–207, doi: 10.1175/1520-0469(1998)055<0186:LLPVAC>2.0.CO;2.

Atkins, N. T., J. M. Arnott, R. W. Przybylinski, et al., 2004: Vortex structure and evolution within bow echoes. Part I: Single-Doppler and damage analysis of the 29 June 1998 derecho. *Mon. Wea. Rev.*, **132**, 2224–2242, doi: 10.1175/1520-0493(2004)132<2224:VSAEWH>2.0.CO;2.

Atkins, N. T., C. S. Bouchard, R. W. Przybylinski, et al., 2005: Damaging surface wind mechanisms within the 10 June 2003
Saint Louis bow echo during BAMEX. *Mon. Wea. Rev.*, **133**, 2275–2296, doi: 10.1175/MWR2973.1.

Botzen, W. J. W., L. M. Bouwer, and J. C. J. M. van den Bergh, 2010: Climate change and hailstorm damage: Empirical evidence and implications for agriculture and insurance. *Resour. Energy Econ.*, **32**, 341–362, doi: 10.1016/j.reseneeco.2009.10.004.

Browning, K. A., and G. B. Foote, 1976: Airflow and hail growth in supercell storms and some implications for hail suppression. *Quart. J. Roy. Meteor. Soc.*, **102**, 499–533, doi: 10.1002/qj.49710243303.

Buban, M. S., C. L. Ziegler, E. R. Mansell, et al., 2012: Simulation of dryline misovortex dynamics and cumulus formation. *Mon. Wea. Rev.*, **140**, 3525–3551, doi: 10.1175/MWR-D-11-00189.1.

Cerniglia, C. S., and W. R. Snyder, 2002: Development of Warning Criteria for Severe Pulse Thunderstorms in the Northeastern United States Using the WSR-88D. Eastern Region Technical Attachment, No. 2002-03, NOAA, Albany, NY, 14 pp.

Chevuturi, A., A. P. Dimri, and U. B. Gunturu, 2014: Numerical simulation of a rare winter hailstorm event over Delhi, India on 17 January 2013. *Nat. Hazards Earth Syst. Sci.*, **14**, 3331–3344, doi: 10.5194/nhess-14-3331-2014.

Craven, J. P., H. E. Brooks, and J. A. Hart, 2002: Baseline climatology of sounding derived parameters associated with deep, moist convection. Proceedings of the 21st Conference on Severe Local Storms, American Meteorological Society, San Antonio, TX, 642–650.

Donavon, R. A., and K. A. Jungbluth, 2007: Evaluation of a technique for radar identification of large hail across the upper Midwest and central plains of the United States. *Wea. Forecasting*, **22**, 244–254, doi: 10.1175/WAF1008.1.

Dudhia, J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.*, **46**, 3077–3107, doi: 10.1175/1520-0469(1989)046<3077:NSOCMD>2.0.CO;2.

Fang, W., G. G. Zheng, and Z. J. Hu, 2005: Numerical simulations of the physical process for hailstone growth. *Acta Meteor. Sinica*, **19**, 93–101.

Fankhauser, J. C., N. A. Crook, J. Tuttle, et al., 1995: Initiation of deep convection along boundary layer convergence lines in a semitropical environment. *Mon. Wea. Rev.*, **123**, 291–314, doi: 10.1175/1520-0493(1995)123<0291:IODCAB>2.0.CO;2.

Farley, R. D., 1987: Numerical modeling of hailstorms and hailstone growth. Part III: Simulation of an Alberta hailstorm—Natural and seeded cases. *J. Climate Appl. Meteor.*, **26**, 789–812, doi: 10.1175/1520-0450(1987)026<0789:NMOHA>2.0.CO;2.

García-Ortega, E., L. Fita, R. Romero, et al., 2007: Numerical simulation and sensitivity study of a severe hailstorm in northeast Spain. *Atmos. Res.*, **83**, 225–241, doi: 10.1016/j.atmosres.2005.08.004.

Gilchrist, B., and G. P. Cressman, 1954: An experiment in objective analysis. *Tellus*, **6**, 309–318, doi: 10.1111/j.2153-3490.1954.tb01126.x.

Grell, G. A., and D. Dévényi, 2002: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophys. Res. Lett.*, **29**, 1693, doi: 10.1029/2002GL015311.

Guo, X. L., and M. Y. Huang, 2002: Hail formation and growth in a 3D cloud model with hail-bin microphysics. *Atmos. Res.*, **63**, 59–99, doi: 10.1016/S0169-8095(02)00019-4.

Harrison, S. J., J. R. Mecikalski, and K. R. Knupp, 2009: Analysis of outflow boundary collisions in north-central Alabama. *Wea. Forecasting*, **24**, 1680–1690, doi: 10.1175/2009WAF2222681.1.

Heymsfield, A. J., A. R. Jameson, and H. W. Frank, 1980: Hail growth mechanisms in a Colorado storm: Part II: Hail formation processes. *J. Atmos. Sci.*, **37**, 1779–1807, doi: 10.1175/1520-0469(1980)037<1779:HMIAC>2.0.CO;2.

Hong, S.-Y., Y. Noh, and J. Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev.*, **134**, 2318–2341, doi: 10.1175/MWR3199.1.

Hong, Y. C., and P. Fan, 1999: Numerical simulation study of hail cloud—Part I: The numerical model. *Acta Meteor. Sinica*, **13**, 188–199.

Huang, X. L., and L. Gao, 2016: Mesoanalysis of a hail process in Taizhou on 19 March 2014. *Meteor. Mon.*, **42**, 696–708. (in Chinese)

Kennedy, P. C., S. A. Rutledge, B. Dolan, et al., 2014: Observations of the 14 July 2011 Fort Collins hailstorm: Implications for WSR-88D-based hail detection and warnings. *Wea. Forecasting*, **29**, 623–638, doi: 10.1175/WAF-D-13-00075.1.

Klemp, J. B., W. C. Skamarock, and J. Dudhia, 2007: Conservative split-explicit time integration methods for the compressible nonhydrostatic equations. *Mon. Wea. Rev.*, **135**, 2897–2913, doi: 10.1175/MWR3440.1.

Knievel, J. C., and R. H. Johnson, 2003: A scale-discriminating vorticity budget for a mesoscale vortex in a midlatitude, continental mesoscale convective system. *J. Atmos. Sci.*, **60**, 781–794, doi: 10.1175/1520-0469(2003)060<0781:ASDVDVF>2.0.CO;2.

Knight, C. A., and N. C. Knight, 2001: Hailstorms. *Severe Convective Storms*, Doswell III, C. A., Ed., American Meteorological Society, Boston, 562 pp.

Kosiba, K., J. Wurman, Y. Richardson, et al., 2013: Genesis of the Goshen County, Wyoming, tornado on 5 June 2009 during VORTEX2. *Mon. Wea. Rev.*, **141**, 1157–1181, doi: 10.1175/MWR-D-12-00056.1.

Kunz, M., J. Sander, and C. Kottmeier, 2009: Recent trends of thunderstorm and hailstorm frequency and their relation to atmospheric characteristics in southwest Germany. *Int. J. Climatol.*, **29**, 2283–2297, doi: 10.1002/joc.1865.

Lee, B. D., R. D. Farley, and M. R. Hjelmfelt, 1991: A numerical case study of convection initiation along colliding convergence boundaries in northeast Colorado. *J. Atmos. Sci.*, **48**, 2350–2366, doi: 10.1175/1520-0469(1991)048<2350:ANCSC>2.0.CO;2.

Levinson, D. H., and R. M. Banta, 1995: Observations of a terrain-forced mesoscale vortex and canyon drainage flows along the Front Range of Colorado. *Mon. Wea. Rev.*, **123**, 2029–2050, doi: 10.1175/1520-0493(1995)123<2029:OOATFM>2.0.CO;2.

Li, B., X. F. Xu, and K. Zhou, 2002: Numerical simulations and Doppler radar data analysis of a hail process in Huaihe River Basin. *Acta Meteor. Sinica*, **16**, 388–400.

Locatelli, J. D., R. D. Schwartz, M. T. Stoelinga, et al., 2002: Norwegian-type and cold front aloft-type cyclones east of the Rocky Mountains. *Wea. Forecasting*, **17**, 66–82, doi: 10.1175/1520-0434(2002)017<0066:NTACFA>2.0.CO;2.

Luo, L. P., M. Xue, K. F. Zhu, et al., 2017: Explicit prediction of hail using multimoment microphysics schemes for a hail-
storm of 19 March 2014 in eastern China. *J. Geophys. Res. Atmos.*, 122, 7560–7581, doi: 10.1002/2017JD026747.

Markowski, P., and Y. Richardson, 2010: *Mesoscale Meteorology in Midlatitudes*. Wiley Press, Chichester, UK, 430 pp, doi: 10.1002/9780470682104.

Markowski, P. M., and Y. P. Richardson, 2017: Large sensitivity of near-surface vertical vorticity development to heat sink location in idealized simulations of supercell-like storms. *J. Atmos. Sci.*, 74, 1095–1104, doi: 10.1175/JAS-D-16-0372.1.

Milbrandt, J. A., and M. K. Yau, 2005a: A multimoment bulk microphysical parameterization. Part I: Analysis of the role of the spectral shape parameter. *J. Atmos. Sci.*, 62, 3051–3064, doi: 10.1175/JAS3534.1.

Milbrandt, J. A., and M. K. Yau, 2005b: A multimoment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description. *J. Atmos. Sci.*, 62, 3065–3081, doi: 10.1175/JAS3535.1.

Miller, P. W., and T. L. Mote, 2017: Standardizing the definition of a “pulse” thunderstorm. *Bull. Amer. Meteor. Soc.*, 98, 905–913, doi: 10.1175/BAMS-D-16-0064.1.

Mlawer, E. J., S. J. Taubman, P. D. Brown, et al., 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res. Atmos.*, 102, 16663–16682, doi: 10.1029/97JD00237.

Nelson, S. P., 1983: The influence of storm flow structure on hail growth. *J. Atmos. Sci.*, 40, 1965–1983, doi: 10.1175/1520-0469(1983)040<1965:TIOSSF>2.0.CO;2.

Niell, S., and K. Walsh, 2005: The impact of climate change on hailstorms in southeastern Australia. *Int. J. Climatol.*, 25, 1933–1952, doi: 10.1002/joc.1233.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.*, 56, 527–530, doi: 10.1175/1520-0477-56.5.527.

Orville, H. D., 1977: A review of hailstone-hailstorm numerical simulations. *Hail: A Review of Hail Science and Hail Suppression*, G. B. Foote, G. B. Knight, Eds., American Meteorological Society, Boston, MA, 49–64, doi: 10.1007/978-1-935704-30-0_2.

Orville, H. D., and F. J. Kopp, 1977: Numerical simulation of the life history of a hailstorm. *J. Atmos. Sci.*, 34, 1596–1618, doi: 10.1175/1520-0469(1977)034<1596:NSOTLI>2.0.CO;2.

Schemm, S., L. Nisi, A. Martinov, et al., 2016: On the link between cold fronts and hail in Switzerland. *Atmos. Sci. Lett.*, 17, 315–325, doi: 10.1002/asl.660.

Shapiro, R., 1970: Smoothing, filtering, and boundary effects. *Rev. Geophys.*, 8, 359–387, doi: 10.1029/RG008i002p00359.

Shuman, F. G., 1957: Numerical methods in weather prediction: II. Smoothing and filtering. *Mon. Wea. Rev.*, 85, 357–361, doi: 10.1175/1520-0493(1957)085<0357:NMIWPI>2.0.CO;2.

Skamarock, W. C., J. B. Klemp, J. Dudhia, et al., 2005: A Description of the Advanced Research WRF Version 2. NCAR Tech. Note NCA/TECH08 STR, NCAR, Boulder, Colorado, USA, 100 pp.

Speer, M. S., L. M. Leslie, L. Qi, et al., 2004: Urban scale modeling: The Sydney hailstorm of 14 April 1999. *Meteor. Atmos. Phys.*, 87, 161–166, doi: 10.1007/s00703-003-0069-0.

Sun, Y. X., and J. Fang, 2013: Numerical study on the initiation of the severe convective weather in Chongqing on 6 May 2010. *Acta Meteor. Sinica*, 27, 364–378, doi: 10.1007/s13351-013-0308-3.

Trier, S. B., W. C. Skamarock, and M. A. LeMone, 1997: Structure and evolution of the 22 February 1993 TOGA COARE squall line: Organization mechanisms inferred from numerical simulation. *J. Atmos. Sci.*, 54, 386–407, doi: 10.1175/1520-0469(1997)054<0386:SASOTL>2.0.CO;2.

Wang, L., C. Zhu, and W.-T. Yu, 2007: Improvement of model forecast on the Asian summer rainfall anomaly with the application of a spatial filtering scheme. *Theor. Appl. Climatol.*, 88, 225–230, doi: 10.1007/s00704-006-0240-x.

Wang, X. M., X. G. Zhou, Z. Y. Richardson, et al., 2016: Discussion on the complete-form vorticity equation and slantwise vorticity development. *J. Meteor. Res.*, 30, 67–75, doi: 10.1007/s13351-016-5040-3.

Wilson, J. W., and W. E. Schreiber, 1986: Initiation of convective storms at radar-observed boundary-layer convergence lines. *Mon. Wea. Rev.*, 114, 2516–2536, doi: 10.1175/1520-0493(1986)114<2516:ICOBAC>2.0.CO;2.

Wilson, J. W., G. B. Foote, N. A. Crouch, et al., 1992: The role of boundary-layer convergence zones and horizontal rolls in the initiation of thunderstorms: A case study. *Mon. Wea. Rev.*, 120, 1785–1815, doi: 10.1175/1520-0493(1992)120<1785:TBLCBC>2.0.CO;2.

Witt, A., and S. P. Nelson, 1991: The use of single-Doppler radar for estimating maximum hailstone size. *J. Appl. Meteor.*, 30, 425–431, doi: 10.1175/1520-0450(1991)030<0425:UODRMS>2.0.CO;2.

Xu, X., M. Xue, and Y. Wang, 2015: Mesovortices within the 8 May 2009 bow echo over the central United States: Analyses of the characteristics and evolution based on Doppler radar observations and a high-resolution model simulation. *Mon. Wea. Rev.*, 143, 2266–2290, doi: 10.1175/MWR-D-14-00234.1.

Yu, X. D., and Y. G. Zheng, 2020: Advances in severe convection research and operation in China. *J. Meteor. Res.*, 34, 189–217, doi: 10.1007/s13351-020-9875-2.

Zhai, G. Q., H. L. Zhang, H. F. Shen, et al., 2015: Role of a meso-γ vortex in Meiyu torrential rainfall over the Hangzhou Bay, China: An observational study. *J. Meteor. Res.*, 29, 966–980, doi: 10.1007/s13351-015-5029-3.

Zhang, C. X., Q. H. Zhang, and Y. Q. Wang, 2008: Climatology of hail in China: 1961–2005. *J. Appl. Meteor. Climatol.*, 47, 795–804, doi: 10.1175/2007JAMC1603.1.

Zhang, D.-L., 1992: The formation of a cooling-induced mesovortex in the trailing stratiform region of a midlatitude squall line. *Mon. Wea. Rev.*, 120, 2763–2785, doi: 10.1175/1520-0493(1992)120<2763:TFMOAV>2.0.CO;2.

Zhang, W. H., and L. Li, 2019: A preliminary application of artificial intelligence on the detection and nowcasting of hail weather. *Acta Meteor. Sinica*, 77, 282–291, doi: 10.11676/qxxb2019.014, (in Chinese)

Zhang, X. L., J. H. Sun, Y. G. Zheng, et al., 2020: Progress in severe convective weather forecasting in China since the 1950s. *J. Meteor. Res.*, 34, 699–719, doi: 10.1007/s13351-020-9146-2.

Zhou, K. H., Y. G. Zheng, B. Li, et al., 2019: Forecasting different types of convective weather: A deep learning approach. *J. Meteor. Res.*, 33, 797–809, doi: 10.1007/s13351-019-8162-6.