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ANALYSIS OF A TORNADO-LIKE SEVERE STORM IN THE OUTER REGION OF THE 2007 SUPER TYPHOON SEPAT

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Abstract: When super typhoon Sepat came close to the Fujian coastline on the night of 18 August 2007 (coded as 0709 in Chinese convention), an associated tornado-like severe storm developed at 2307–2320 Beijing Standard Time in Longgang, Cangnan County, Wenzhou Prefecture, Zhejiang Province approximately 300 km away in the forward direction of the typhoon. The storm caused heavy losses in lives and property. Studying the background of the formation of the storm, this paper identifies some of its typical characteristics after analyzing its retrieval of Doppler radar data, vertical wind shear and so on. Synoptic conditions, such as unstable weather processes and TBB, are also studied.

Key words: tornado-like severe storms; radar characteristics; observation

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1 INTRODUCTION

Although small in scale, tornados, also referred to as whirlwinds, are the most violent storms that come with vigorous rotational force. A tornado is a funnel-like cloud body spiraling downwards from a cumulonimbus base, or a cloud of dust whirling upwards from the surface. Similar to moving whirling storms, tornados are so intense that they destroy trees, buildings, and ships along their paths. For their genesis, tornadoes depend on the following conditions: 1) unstable low-level warm air, 2) a tower-shaped cumulonimbus in the unstable air, and 3) upper and lower levels with opposite wind directions, allowing the removal of lifted air[1]. Due to the heavy damage caused by tornados, their study is of great importance in minimizing losses in industrial and agricultural production, building industry, and people’s livelihood and properties, in disaster prevention and mitigation, and in fostering social security.

China’s scientists have devoted much effort to tornado research since the 1980s[2, 3], with encouraging results. However, thus far, no general summaries have been presented. Summing up what has been achieved in order to gain insights of the previous work and to shed light on future research directions is therefore necessary. A lot of papers propose two aspects that summarize tornado research in China over the past 30 years: 1) the achievement of scientific results, ranging from immediate, post-event surveys of tornado destructions to the analysis of related climate background and, furthermore, to investigations into the structure of the tornado along with its formation mechanism, as undertaken in recent years with considerable success; and 2) the improvement of techniques, ranging from simple surveys of facts to statistical summary of weather characteristics, and from the use of conventional station data to the application of satellite and Doppler radar observations (mainly in recent years), as well as profiles for exploring tornado properties. Specifically, numerical models such as Weather Research and Forecast (WRF) and Atmospheric Research Prediction System (ARPS) are employed for these purposes.

In China, few studies have been conducted on tornados induced at the outer region of tropical cyclones. For example, Shen[4] published research on the characteristics and genesis causes of tornados in front of typhoons in the province of Jiangsu. Similarly, Chen[5] made a detailed physical analysis of a tornado that occurred on September 6, 1999. Huang and Zhang[6] addressed the causes of intense convective weathers at the outer regions of typhoons. Lin and Li[7], Lin[8], and Mai[9] presented studies regarding tornadoes hitting some parts of the Pearl River delta due to Typhoon Tim (9406), a severe tropical storm

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that exerted influence at its outer regions. These analyses of tornados in front of typhoons show that tornados are always along the right-front side in the direction of the typhoon movement, and that they are associated with the typhoon's intensity and other factors, such as sufficient amount of water vapor and slopes in the vorticity equation.

The authors of this study have found no tornado studies on the thermal or dynamic characters induced by the peninsular effect, orographic terrain, and land-sea thermal contrast; however, there have been some preliminary studies documented by Ji and Zhan[10], and Gandikota et al[11].

Tornados are complex; however, there are few studies on tornados around the world. Hence, there are many hypotheses and models on the formation of tornados. For example, Shcherbinin[12] proposed an electromagnetic mechanism for the occurrence of tornados. A number of researchers, including Yanitskii[13], have linked the process of tornado formation to fractures in the earth's crust. Nikulin[14] considered a thermal mechanism of tornado formation, thereby proposing that the intensified rotation of a liquid substance over a heated surface can be used to model atmospheric vortices. Meanwhile, Mcbean[15] outlined tornado risk management strategies.

While it is difficult to accurately predict the location of typhoon-induced tornadoes and the time of outbreak in the area of an on-land hurricane, Verbout[16] showed that strong hurricanes are more likely to cause tornados to break out than weaker ones, and that low-level shears favor the formation of tornados. Rao[17] found that the degree of low-level baroclinicity seems to play an important role in the formation of tornados. In addition, tornados are produced accordingly on the inward side of the inner and outer regions of spiral rainbands.

There are few studies on the interaction of the tornados with boundary layer features, such as peninsulas, mountains, and land-sea thermal contrast. Simpson et al.[18] held that tornados occur when intense horizontal vortex tubes in the lower part of the boundary layer suddenly become vertical. Raddatz[19] asserted that atmospheric boundary layer moisture affects the magnitude of the potential energy available for deep convection and the seasonal pattern of tornado variations. Wu[20] considered a tornado to be the result of interactions between low-level jets and synoptic-scale flows.

2 RELATED WEATHER BACKGROUND

The tornado-like severe storm of interest (to be refered to as the "storm" hereafter) was produced in a rainbelt at the periphery of Sepat. At 2000 Beijing Standard Time (BST) on 18 August 2007, the ridge line of the Western Pacific subtropical high (subtropical high hereafter) was approximately at 32° N. It stretched into the continent as an east-west band, with the typhoon's center being close to the Fujian coast, and Longgang being under the control of the circulation at the periphery of Sepat (Fig. 1). Between the subtropical high and the typhoon, vast amounts of vapor were transferred into the air above the town. Prior to the outbreak of the tornado, the eastern coastal zone of China was under the effect of warm air without any southward incursion of cold air. The storm occurred on the front-right side in the direction of Sepat's movement; its effect is shown in Fig. 2.

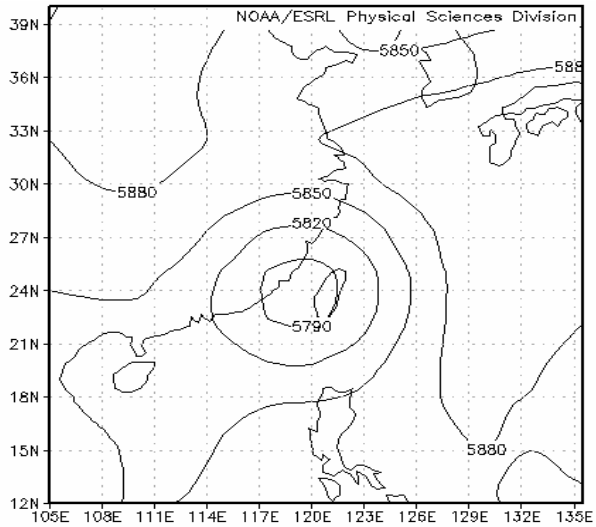

Fig. 1. Situation at 500 hPa for 2000 BST on 18 August 2007.

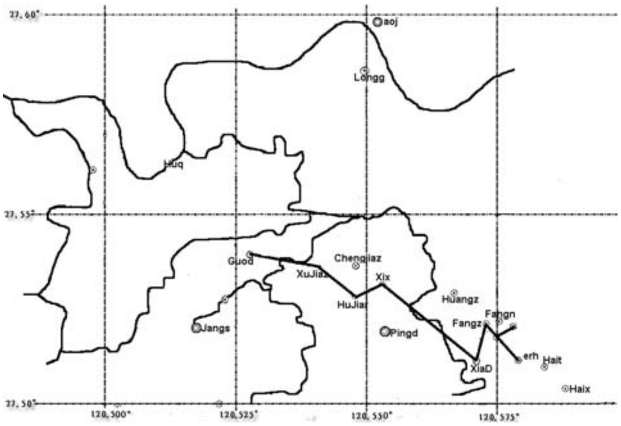

Fig. 2. Path of the tornado-like severe storm induced by Sepat

3 DESCRIPTION OF THE DAMAGE CASUED BY THE TONADO-LIKE SEVERE STORM

A post-event investigation has the following findings: (1) Civilian houses collapsed in narrow stripes without obvious damages to those next to them. A SEE-NWW-oriented stripe connected all hit villages with a width of around 200 m (by visual measurement), 60–70 m at the narrowest point, and a length of about 8 km. (2) The storm did not last long. According to the recall by witnessing villagers, the earliest village hit was Erhe (around 2310 BST) and the last was Guoshi (around 2320 BST), indicating a duration of a little more than 10 minutes. As claimed by a large number of wintesses, the storm was accompanied by red fire balls (columns) moving swiftly and sounds like bullets shooting past. (3) Based on the introduction to tornadoes in *Prediction and Pre-Warning of Meteorological Disasters and Scientific Countermeasures for Disaster Mitigation in China* co-edited by HUANG Rong-hui and ZHANG Qing-yun, and what is shown in terms of wind force and the severity of destruction at the spot, this storm should be within F2–F3 in the Fujita scale for tornado categorization[10]. The destruction is described in more detail below. A total of 156 civilian houses collasped, 11 people were killed (of whom three were severely injured and dead later) and sixty were injured (six of them seriously) in the villages of Xujiazhuang, Qincun, Erhe, Xiadongzhuang, Fangzhong and Xixian in the town of Longgang. Solidly built brick and concrete houses fell down and the roof and tiles were overthrown. A iron-casing ship capable of carrying 18 tons of freight was lifted up by the strong wind to lie on top of a house. A truck loaded with five tons of goods was turned over and dislocated. Power lines were broken off half way on the poles. A 139-year old camphor tree inside a temple was toppled (Fig. 3).

Fig. 3. Scenes of the aftermath of the tornado-like storm hit

4 DOPPLER RADAR OBSERVATIONS FOR THE WENZHOU REGION

The Longgang storm was formed when two parallel and short bands of intense rain in a spiral rainband at the periphery of the typhoon merged into one band during their westward movement, leading to the gradual merger between the two and the redistribution of energy. Due to their proximity to the coast and topographic lifting, the approaching typhoon resulted in an east-west vigorous convergence zone at low levels and caused the entry of a vortex cell into the zone. The vortex cell soon became a super cell. It then evolved into a super storm cell because of convergence and ascending motion.

4.1 *Retrieval of Doppler radar data by a 4VAR assimilation technique*

The storm was 40 km away from the radar station of Wenzhou; thus, the data can provide good retrieval. Data were taken from two neighboring volume-scanned cells at 6-min. intervals, covering an area of 100×100×1.8 km^3, with the horizontal (vertical) resolution of 2 km (300 m). The retrieval of such data at 2243–2307 BST showed that to the right were the meso-β southeast jets, with strong shears of vertical wind direction/velocity from lower to middle levels, and with the wind changing from southeasterly to easterly, and then northerly, thereby forming a high-value horizontal vorticity region in favor of the genesis of the studied storm. There were more than one intense meso-γ convective cells inside the meso-β spiral rain belts. One meso-γ vortex was always available on the southern side of related cells A and B at the middle to lower levels (Fig. 4), with subsidence ahead of and behind it. Its horizontal vorticity reached the value of a mesocyclone. Inside it, airflows converged to make vorticity more concentrated, producing an even stronger horizontal component of vorticity, which was then changed to a vertical component of vigorous vorticity favorable to the formation of the storm. Viewed from the retrievals, intense storm-associated meso-vortex features occurred 20–30 min. ahead of the storm. The retrievals were found to be in agreement with the products of the next-generation weather radar for identifying the evolution of mesocyclones.

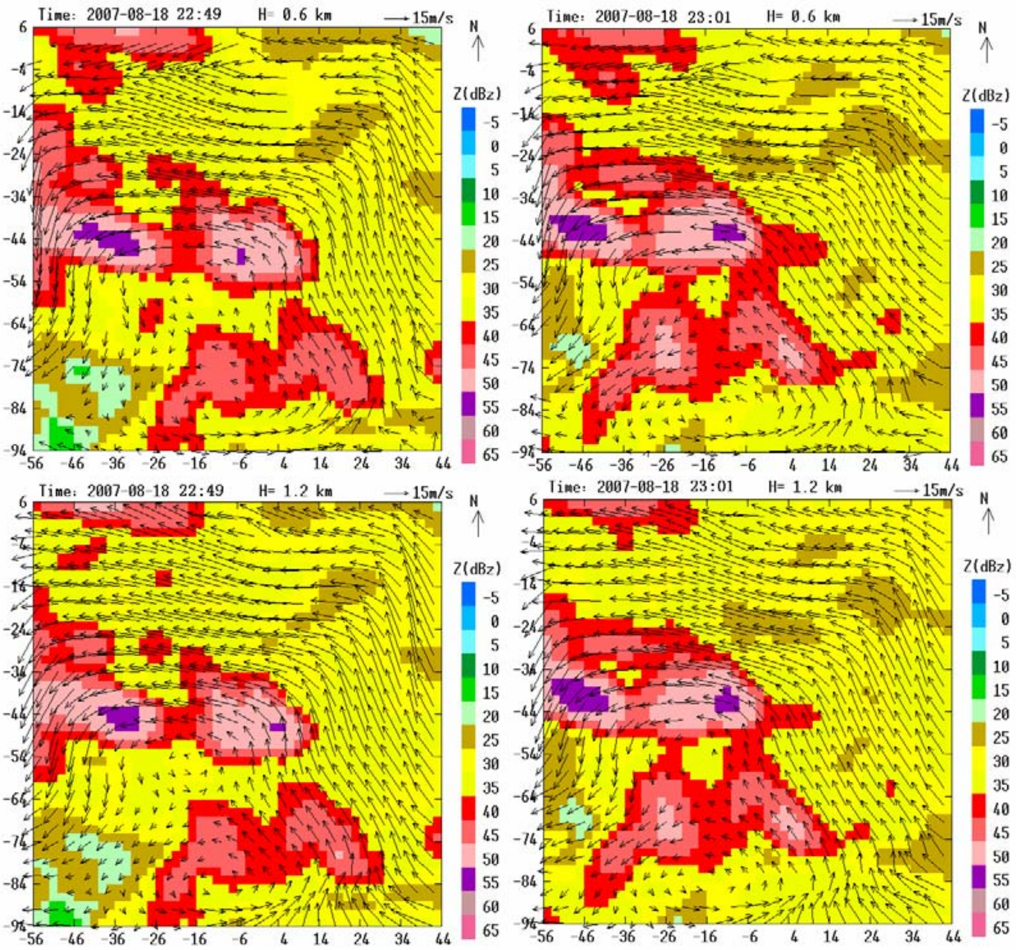

Fig. 4. Retrieved wind field overlaid by reflectivity (z = 0.6; 1.2 km above the ground)

4.2 *Features of the vertical wind shear*

The Doppler radar station of the Wenzhou prefecture was 42 km away from Longgang. Thus, the wind field above the station can represent the one above it. The features of a vertical wind shear (Fig. 5) can be discovered through wind profile charts. Fig. 5 shows that the vertical wind shear at 700–2700 m was strong at 1900 BST; however, it did not acquire its strongest intensity until 2215 BST. At 2215 BST, the surface wind was NE (10 m/s), and the wind at 2700 m was SE (22 m/s).

5 DIVERGENCE OF WATER VAPOR FLUX AND TBB-BASED DIAGNOSIS

The 850-hPa divergence of water vapor flux was positive at 0800 BST August 18th (figure omitted) and became negative at 1400 BST (Fig. 6a), suggesting the presence of a significant convergence of water vapor (displayed as a wet tongue) prior to the onset of this storm; the water vapor supply provided main energy for the formation of this storm. By 2000 BST, the positive divergence of water vapor flux advanced southward and Longgang was at the border between positive and negative water vapor flux, where the narrow wet tongue interacted with a dry area to the north to form humidity gradients (Fig. 6b). It was just at a large-value area of the gradients that this storm took place. The convergence of water vapor can result in the motion of severe convection (which can be depicted by the value of TBB). As found in a number of airborne experiments on severe storms in which Fujita took part, enormous differences exist in wind speed in different portions of the cumulonimbus and they can be even larger when two of such clouds approach each other. As what Ding has pointed out, if the speed shear (differences in direction or measured value) is intense between strong ascending and descending airflows existent between the cumulonimbus or between the cumulonimbus and the air right next to it, a vortex can form and further evolve into a tornado. At 2000 BST August 18, no clouds were found along the coast of the area connecting the Zhejiang and Fujian provinces. At 2100 BST, small patches of clouds appeared and kept strengthening at 2200 BST with the coverage extending NW-SE into Cangnan (Fig. 6c). The intensity of clouds became explosively intense at 2300 BST that two highly convective clouds, with TBB (cloud-top temperature) ranging from -70° C to -80° C, were approaching toward each other and merging into one at 2400 BST. It was right at the transitory zone between the two clouds that this storm took place. The TBB-based observational facts agree with the viewpoints of the above two scholars.

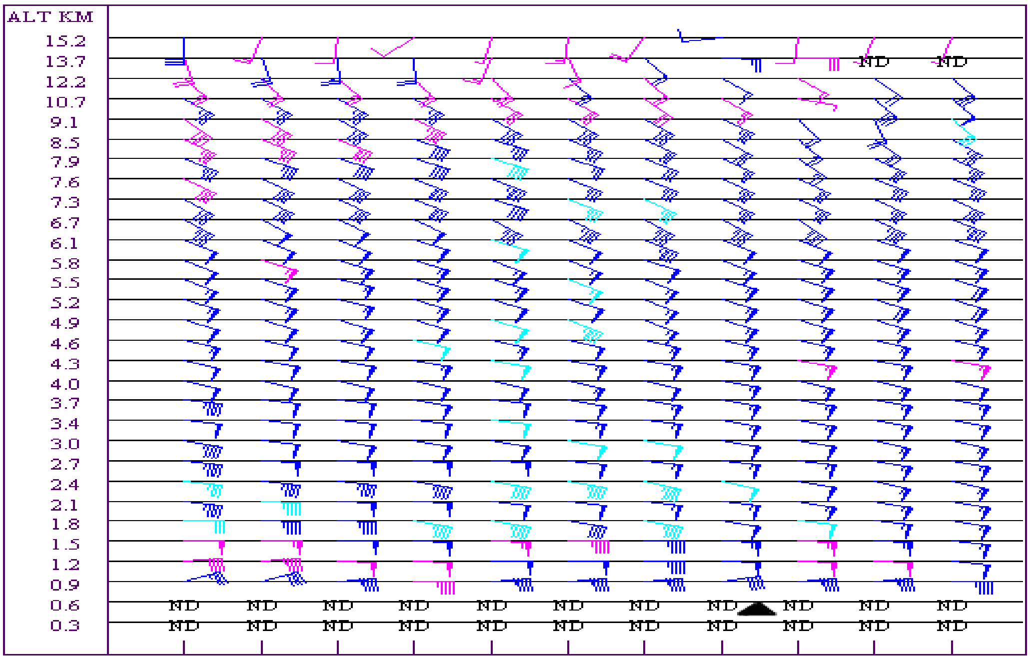

Fig. 5. Wind profile chart at 2100–2200 BST on 18 August 2007 (black triangle is at 2215 BST)

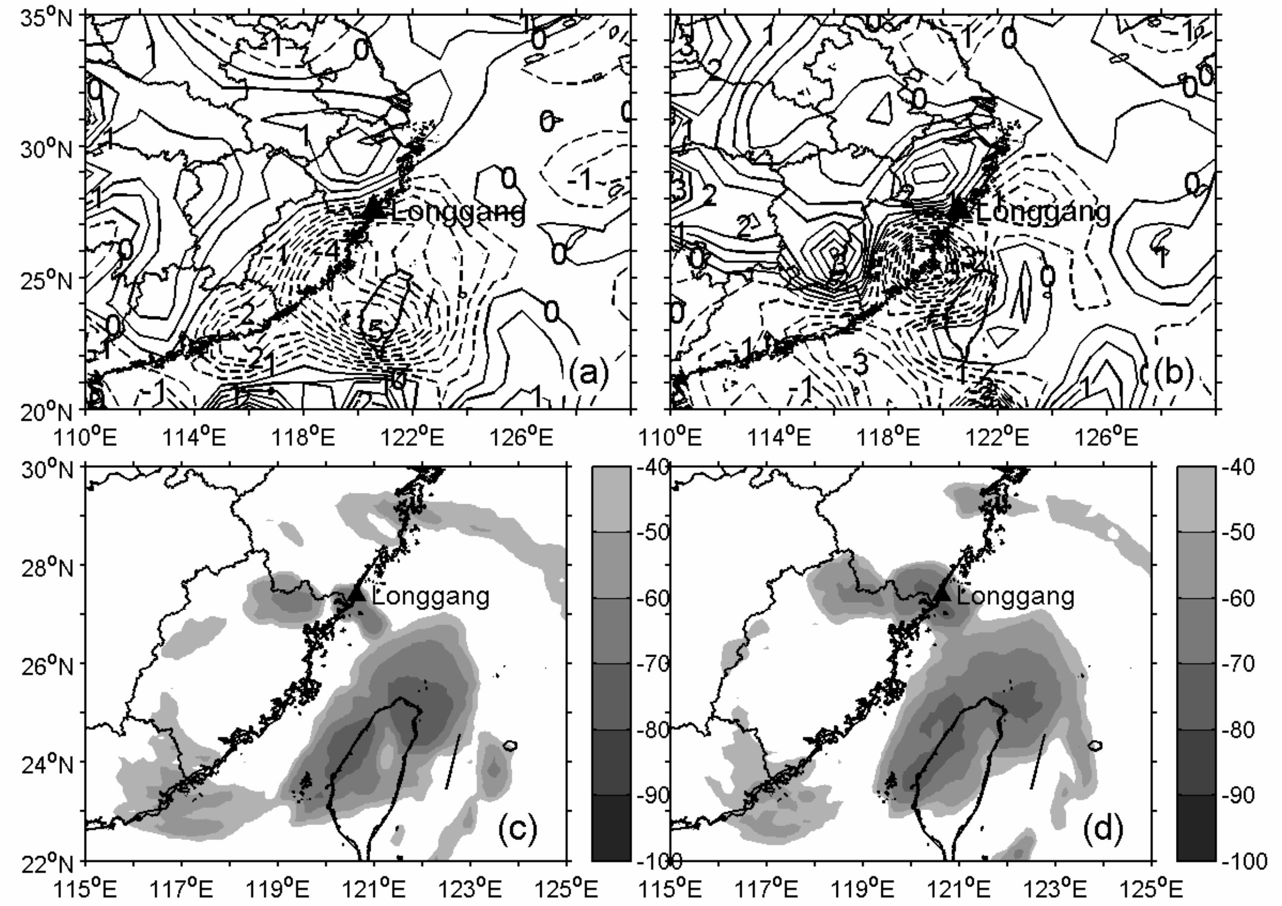

Fig. 6. (a) Divergence of 850-hPa water vapor flux at 1400 BST August 18, 2007 (Unit: 10^{-7}g/(cm^2) hPa s); (b) Same as (a) but for 2000 BST; (c) Minimum cloud-top TBB at 2200 BST August 18, 2007 (Unit: ° C); (d) Same as (c) but for 2300 BST

6 SUMMARY

From the foregoing analysis, we come to the following conclusions:

(1) Storms that cause damages above the F2 scale tend to be associated with super cells. Therefore, users of Doppler radars in detecting tornadoes should pay close attention to and perform a careful analysis of the factors of reflectance, vertical wind shear, and storm-relative radial speed, apart from synoptic conditions (e.g., unstable weather processes and vertical wind shears), in order to discover the characteristics typical of tornadoes (e.g., pixel-to-pixel velocity shears and mesocyclones). In particular, a mesocyclone at lower levels is closely related to a tornado.

(2) In the continuous tracking of storms with Doppler, caution should be exercised to see if a micro-vortex is in the process of genesis and evolution, and if more of such vortices will merge and result in a bigger one. When carried by rapid updraft generated by the mother convective cell, the bigger vortex is likely to become a tornado.

(3) Other characteristics, such as unstable weather effect and thermal effect, can reinforce typhoon-induced storms.

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