Environmental analysis on the first documented tornado outbreak in China

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Abstract
This study presents an analysis on the storm environmental features during the first recorded tornado outbreak in the modern history of China on August 13–14, 2018. Eleven reported tornadoes were spawned within a 20-hr period by Typhoon Yagi (1814) during its dissipating stage after its landfall. They primarily formed when Yagi was at a relatively weak intensity. Six tornadoes were generated after that Yagi had lost its intensity as a tropical depression. These tornadoes were mainly located in the northeast quadrant with respect to the typhoon center. Specifically, they were concentrated in the overlapping region of the large storm relative helicity (SRH) and large entraining convective available potential energy (E-CAPE) that considers the effects of the environmental air entrainment. The intrusion of midlevel dry air was responsible for the spatial pattern of large-value E-CAPE. Special focus was further put into the dynamical diagnosis of the cause that the maxima in SRH were distributed in Yagi’s northeast sector. On cylindrical coordinates, the northeast quadrant was characterized by the strongest upward increase in the radial velocity in a layer of 950–700 hPa, which resulted from the interaction between the typhoon circulation and the subtropical high and a midlevel trough. The resultant in-up-out radial wind profile contributed to the large helicity in the northeast quadrant. In the lowest 50 hPa layer, the helicity was mainly owed to the upward increase in the tangential velocity associated with typhoon vortex. The diagnoses of the atmospheric environment for the tornado outbreak in this case may provide additional benefit for assessing the tornado risk within landfalling tropical cyclones in China.

Keywords
China, tornado, tornado outbreak, tropical cyclone

1 | Introduction

Tornadoes are violently rotating columns of air that extend downward from thunderstorms to the ground and thus are destructive to lives and properties. Particularly, the occurring of multiple tornadoes in close proximity in time and space may create more severe damage and fatalities. For instance, Schneider et al. (2004) documented...
that the outbreaks of tornadoes account for over 80% of all tornado-related fatalities in the United States. A tornado outbreak event is defined herein as “multiple tornado occurrences associated with a particular synoptic-scale system” (American Meteorological Society, 2021) and generally consists of 10 or more tornadoes (Galway, 1977). An improved understanding of the formation environment of tornadoes during an outbreak event may lend support to the disaster management policy and mitigation strategy.

In contrast to the United States, China has much fewer tornado outbreak events. To the best of our knowledge, the only one tornado outbreak recorded in the modern history of China occurs in the envelope of Typhoon Yagi during August 13–14, 2018 (Bai et al., 2020). Eleven confirmed tornadoes were spawned by Yagi within a period of 20 hr after its landfall in central eastern China. In fact, landfalling tropical cyclones (hereinafter referred to as TCs) are one of the synoptic systems that often induce tornado outbreaks. As documented by Edwards (2012), the top 10 TC tornado producers in the United States spawned 744 tornadoes in total. Although faced with more landfalling TCs than the United States (Lyons, 2004; Zhang et al., 2009), China suffers much fewer TC tornadoes. During 2006–2018, an annual average of five TC tornadoes was reported in China (Bai et al., 2020). These tornadoes preferentially formed in coastal areas with flat terrains in central eastern and southern China. By contrast, the recorded TC tornadoes have an annual number of 73 in the United States during 1995–2010 (Edwards, 2012). The reported 11 tornado occurrences produced by Typhoon Yagi in 2018 appears to noticeable, which deserves to be penetratingly explored.

Previous studies suggested that mid-troposphere dry air intrusions are an important factor for the tornado outbreaks associated with landfalling TCs (Curtis, 2004). The intrusion of dry air is believed to destabilize the storm environment by steepening the lapse rate through the midlevel evaporative cooling and increasing surface heating. Sueki and Niino (2016) also documented that the convective available potential energy (CAPE) which considers the effect of the entrainment of environmental air (entraining-CAPE or E-CAPE) exhibits a good performance on accounting for the spatial distribution of TC tornadoes. In the dynamic perspective, TC tornadoes tend to occur in the northeast quadrant where typifies an environment with enhanced low-level shear and storm-relative helicity (SRH) which aid in providing the necessary rotation for the formation of mesocyclone and tornado (McCaul, 1991).

A primary motivation for this paper is to document the large and mesoscale atmospheric characteristics during the aforementioned tornado outbreak event in central eastern China. Special focuses are put into the analysis of the atmospheric conditions that are conducive for tornadoes in TC envelopes, including the low-level environmental helicity, thermodynamic instability, and midlevel dry air intrusions. A detailed dynamic diagnosis on the spatial pattern of low-level environmental helicity is also presented.

2 | CASE OVERVIEW

Typhoon Yagi made landfall in eastern China at 1530 UTC (UTC = local time –8 hr) on August 12, 2018 at an intensity of severe tropical storm (24.5–32.6 m s⁻¹). It then moved toward the northwest inland and rapidly weakened to be a tropical storm (17.2–24.4 m s⁻¹) in the following 2 hr. At 0950 UTC on August 13, the first reported tornado, rated EF3 (Yao et al., 2019), formed in a squall line located approximately 700 km to the due north of the TC center (refer to the northernmost green triangle in Figure 1). During the following 9 hr, four tornadoes were spawned to the south of the southern border of Shandong Province (refer to the southernmost green triangles in Figure 1). After 2100 UTC on August 13, Yagi lost its intensity as a tropical depression. Although at a relatively weak stage, Yagi spawned six tornadoes in the northern coastal area of Shandong Province from the late morning to early afternoon (0200–0530 UTC) on August 14 (refer to the magenta triangles in Figure 1). Prior studies suggested that strong TCs are more likely to generate tornado outbreaks than weak TCs (e.g., Verbout et al., 2007). In the current case, all the reported tornadoes were produced during the weak TC stage. It is possible that Yagi may have produced more tornadoes in its stronger intensity before the landfall while this cannot be confirmed due to the lack of witness at sea.

During this tornado outbreak event, 9 out of the 11 tornadoes were produced in the northeast quadrant with respect to the center of Typhoon Yagi. For most of these tornadoes, ground surveys with the aid of drones were conducted by teams affiliated with the Chinese Academy of Meteorological Sciences, the Foshan Tornado Research Center, and some local meteorological bureaus (Yao et al., 2019). It is worthy of noting that the last six tornadoes were located in close proximity in space and time (during a 2.5-hr period). Considering that these six tornadoes formed in a short time period and were located in close proximity in space, the author primarily focuses on the atmospheric conditions near the formation time of these tornadoes in the following section. The data obtained from the Himawari-8 satellite (Bessho et al., 2016) and the fifth generation of ECMWF atmospheric reanalysis (ERA5) (Hersbach et al., 2020) at 0500 UTC on August 14 were used to represent the atmospheric conditions.
conditions for these tornadoes. The ERA5 reanalysis data are hourly available at a horizontal resolution of 0.25°.

3 | ANALYSIS ON ATMOSPHERIC CONDITIONS

3.1 | Thermodynamic instability

A TC’s interior is usually covered by clouds or precipitation and thus the thermodynamic instability for TC tornado formation is generally limited compared to the midlatitude counterparts (McCaul, 1991). Figure 2a shows that the eastern semicircle of Yagi is characterized by moderate CAPE. Here the CAPE is calculated by assuming the lifted air parcel has an initial potential temperature and mixing ratio averaged over the mixed layer (lowest 1,000 m above ground level) and integrating the buoyancy (B) between the level of free convection (LFC) and the equilibrium level (EL) of the air parcel:

$$\text{CAPE} = \int_{\text{LFC}}^{\text{EL}} Bdz \approx g \int_{\text{LFC}}^{\text{EL}} \frac{T_{vp} - T_{ve}}{T_{ve}} dz,$$

where $T_{vp}$ and $T_{ve}$ are the virtual temperature of the air parcel and the environmental virtual temperature, respectively. Although the six tornadoes of interest were located in the zone with moderate conditional instability, there was a large fraction featured by greater CAPE values in the southeast quadrant (Figure 2a). It is thus difficult for forecasters to use CAPE to assess the tornado risk in such a large spatial coverage.

When the entrainment of environmental dry air is considered, the computation of $T_{vp}$ in Equation (1) needs to be updated starting at the level of condensation (LCL) to obtain the E-CAPE. For simplicity, the parcel is usually assumed to be mixed with a fixed fraction $\varepsilon$ (% km$^{-1}$; entrainment rate with height) of environmental air. The updated $T_{vp}$ of the resulting mixture is determined by the new profile of equivalent potential temperature $\theta_{ep}$ for the air parcel (e.g., Jensen and Del Genio, 2006),

$$\frac{d\theta_{ep}}{dz} = -\varepsilon(\theta_{ep} - \theta_e),$$

where $\theta_e$ represents the environmental equivalent potential temperature. In the present study, the E-CAPE was calculated following the work in Sueki and Niino (2016) and assuming a constant mass entrainment rate of 40% km$^{-1}$ (Bai et al., 2020). Figure 2c shows that the large-value (exceeding 50 J kg$^{-1}$) area of the E-CAPE is concentrated in the northeast quadrant, generally consistent.
with the tornado locations. In contrast to the ordinary CAPE, the E-CAPE in the southeast quadrant is marginal (Figure 2a,c). For the rest five tornadoes formed on August 13, 2018, the four tornadoes that were located in the TC’s northeast quadrant were characterized by an E-CAPE value of at least 40 J kg\(^{-1}\) (not shown).

The E-CAPE is demonstrated to be sensitive to the humidity in the midtroposphere (Molinari et al., 2012). From the water vapor channels of the Himawari-8 satellite, a distinctly dry environment near 400 hPa covers a large fraction of the area to the south of the tornado locations (Figure 1b), indicating clearly dry air entraining for lifted air parcels. The buoyancy of air parcels would be reduced because of the decreased equivalent potential temperature due to the entrainment of dry air, ultimately leading to small magnitudes of E-CAPE. In this perspective, the dry air intrusion in the midtroposphere tends to reduce the E-CAPE, although it may aid in the enhancement of the CAPE (Vescio et al., 1996; Curtis, 2004). In the presence of midlevel dry intrusions in this case, the diagnoses of the thermodynamic instability that considers entrainment effect seem to be much better than the ordinary CAPE for assessing the tornado potential.

Figure 3 shows that the tornado zones were characterized by pronounced moisture horizontal gradients in the layer from 400 to 200 hPa. The minima in relative humidity (RH) in the proximity upwind region of these tornadoes were even below 20% (Figure 3a). To the south of the tornado zones, the upwind dry-air layer above 500 hPa featured a low RH generally less than 50%
Under the consideration of entrainment, the buoyancy of lifted air parcels would be sensitive to the dry air intrusion in this layer and thus a reduced conditional instability (i.e., E-CAPE) was obtained. Curtis (2004) examined the tornado outbreaks associated with the landfalling TCs from the Atlantic and Gulf of Mexico during 1960–1999, 11 of the 13 identified TC cases showed that tornado outbreaks occurred in the regions with a sharp gradient at 700 hPa and/or 500 hPa. In the present case, the most prominent moisture gradients occurred on higher levels at 400–200 hPa (Figure 3b). The dry air intrusions are believed to enhance the surface heating due to the inhibition of stratiform cloud formation in that region (e.g., Figure 1a) and thus be beneficial to the erosion of any convection inhibition. It is important to note that tornado outbreaks can also take place without dry air intrusions aloft within landfalling TCs. For instance, Curtis (2004) documented that 2 of the 13 tornado outbreak TC cases did not show a clear evidence of midlevel dry air intrusions.

3.2 Storm-relative helicity

The storm-relative helicity is closely related to streamwise vorticity and thus a measure of the potential for cyclonic updraft rotation in right-moving supercells (Davies-Jones, 1984). Large values of the SRH calculated for the lowest 1 and 3 km layers above ground level usually suggest an increased threat of tornadoes (Markowski and Richardson, 2010). In the present study, the SRH was calculated by integrating the storm-relative streamwise vorticity from ground to the heights \( h \) of 1 and 3 km, respectively,

\[
\text{SRH} = \int_0^h \left( \mathbf{V} - \mathbf{C} \right) \cdot \left( \mathbf{k} \times \frac{\partial \mathbf{V}}{\partial z} \right) dz,
\]

where \( \mathbf{V} \) and \( \mathbf{k} \) represent the horizontal wind vector and the unit vector in the vertical direction, respectively. The storm motion vector \( \mathbf{C} \) was estimated following the methods suggested by Bunkers et al. (2000).

Distinctly large-value areas of 0–3 km SRH (greater than 200 m\(^2\) s\(^{-2}\)) and 0–1 km SRH (greater than 100 m\(^2\) s\(^{-2}\)) were located in the northeast quadrant covering the tornado locations (Figure 2b,d). The presence of such enhancing low-level SRH indicates that significant streamwise vorticity was available in that region for tilting into the vertical, which aids in producing numerous rotating updrafts and thus increases the threats of supercells and tornadoes (Markowski and Richardson, 2010). The large SRH in the tornado zone was a result of the distinct “horseshoe” shape hodograph (Figure 4a)
which resembles to the composite hodograph for the U.S. TC tornadoes analyzed in McCaul (1991). Strong veering winds and shear existed from surface all the way to above 16 km altitude. The strongest horizontal winds occurred near 3–4 km altitude. The magnitude of SRH can be graphically estimated by twice the area bounded by the hodograph curve and the tip of storm-motion vector (Markowsk and Richardson, 2010). In the present case, the hodograph structure as shown in Figure 4a aids to provide a substantial positive SRH. For the rest five tornadoes formed on August 13, 2018, four of them were located in an environment with the 0–1 km SRH exceeding 120 m s\(^{-2}\) (not shown). In particular, three tornadoes were located immediately close to the maxima in the SRH magnitude.

In this tornado outbreak event, it is noteworthy that SRH and E-CAPE appear to contribute to the tornado potential in a complementary manner. The tornado occurrences are distributed in the overlapping area of the large-value SRH and E-CAPE (Figure 2b–d). This result appears to be consistent with the findings of Sueki and Niino (2016) in which the location centroid of the tornadoes from 34 typhoons in Japan were located between the maxima in the distributions of the composite E-CAPE and 0–3 km SRH. It seems that a combination of SRH and E-CAPE may be a good indicator for forecasters to assess tornado potential on TC rainbands. It is important to note that 10 hr before the formation of the six tornadoes of interest, the average E-CAPE and 0–1 km SRH over the tornado zone had already exceeded a magnitude of 40 J kg\(^{-1}\) and 100 m\(^{-2}\) s\(^{-2}\), respectively. These tornadoes formed as the approaching of the midlevel dry air intrusions, as indicated by the sharp drop of RH in Figure 4b.

### 3.3 Diagnosis of environmental helicity on cylindrical coordinates

To understand why the large SRH was locally concentrated in the northeast quadrant, a diagnosis of environmental helicity was further conducted on cylindrical coordinates inspired by Molinari and Vollaro (2008). It is suggested that the diagnosis of total helicity on cylindrical coordinates aids in explaining the dynamic contribution to storm-relative helicity. Following the framework in Molinari and Vollaro (2008), the author herein begins with the cylindrical coordinate form for total helicity (Xu and Wu, 2003):

\[
H_T = -\frac{v_r}{\partial Z} + v_t \frac{\partial V_r}{\partial Z},
\]

where \(v_r\) and \(v_t\) represent the radial and tangential velocity components, respectively, and the vertical term in the helicity expression has been neglected (Molinari and Vollaro, 2008). Equation (4) indicates that large total helicity is expected in layers with upward increase in the radial velocity component (the second term on the right…
of the equation) because the tangential velocity in TC is always large (Molinari and Vollaro, 2010).

Figure 5 shows the vertical distributions of radial and tangential velocities averaged over the four quadrants with respect to the Yagi center. The differences of radial velocity in the four quadrants are dramatic. A marked upward increase in the low-level radial wind is located in the northeast quadrant (Figure 5a). This quadrant is
characterized by shallow inflows in the layers of the lowest 100 hPa and outflows aloft. Different from the rest quadrants, such a radial wind profile (e.g., in-up-out flow structure) leads to the positive helicity in the northeast quadrant. According to Equation (4), the positive helicity is large where positive tangential winds multiplied positive gradients in radial wind. Figure 5e–h shows that the northeast quadrant features greater positive tangential winds beyond 200 km of the Yagi center at lower levels than those in the rest quadrants. As a result, the term $v_r \frac{\partial v_r}{\partial z}$ produces largest helicity in the northeast quadrant (Figure 4a).

It is worth to note that the near-ground layers are characterized by negative helicity within 400 km of the Yagi center (Figure 6a). Such negative values are believed a result of the deceleration of inflow due to the friction on land surface. However, the term $-v_r \frac{\partial v_r}{\partial z}$ produces large positive helicity in the near-ground layers (Figure 6b) due to the radial inflows and upward increase in tangential winds (Figure 5a,e). By adding these two terms, prominently large positive helicity exhibit in the entire lowest 300 hPa layers in the northeast quadrant. As suggested by Molinari and Vollaro (2008, 2010), such reasoning extends to storm relative helicity as well.

To investigate why the northeast quadrant is characterized by the in-up-out wind profile, the large-scale ambient flows were further examined after applying a vortex removal technique described in Kurihara et al. (1990, 1993). Figure 7 shows that Yagi is located near the western ridge of the subtropical high (labeled “H” in blue) and to the south of the 500-hPa trough (solid curve in black). Yagi recurved toward the northeast along the resultant steering flows under the interaction of the east-moving midlevel trough and the steering of the subtropical high. Influenced by such synoptic patterns, strong midlevel ambient southwesterlies were located in the northeast sector of the original Yagi center (Figure 7). On cylindrical coordinates, these ambient southwesterlies would contribute to the midlevel outflows from the Yagi center in the northeast quadrant. Consequently, the interactions between the typhoon circulation and the midlevel trough and the subtropical high ultimately produced the large SRH values in the northeast quadrant of Yagi. Verbout et al. (2007) showed that the tornado outbreaks within the landfalling hurricanes that affected Texas were closely associated with midlatitude 500-hPa troughs which help to recurve the landfalling hurricanes back toward the northeast. In addition to the midlevel trough in the current case, the subtropical high also supported the Yagi’s northeastward recurvature, providing enhanced low-level shear and helicity for the formation of mesocyclones and tornadoes.

4 | CONCLUDING REMARKS

The tornado outbreak during August 13–14, 2018 in central eastern China was analyzed through the ERA5 reanalysis data and satellite observations. This is the first documented tornado outbreak in the modern history of China. During this event, a total of 11 tornadoes were spawned by Typhoon Yagi within a 20-hr period. Ten out of the 11 tornadoes occurred in the northeast quadrant with respect to the Yagi center. All the reported tornadoes were generated during the TC’s dissipating stage after making landfall. In particular, six tornadoes formed when Yagi had lost its intensity as a tropical depression on August 14, 2018. Considering that these six tornadoes successively formed in a short time period of only 2.5 hr and were located in close proximity in space, the

![Figure 6](image-url)  # Figure 6  The total helicity averaged in the northeast quadrant in the forms of the two terms on the right of Equation (4) as described in the text. The calculations were performed at 0500 UTC on August 14, 2018. The Yagi center is denoted by 0 km at the x-axis.
environmental analysis was primarily conducted near the formation time of these tornadoes.

The thermodynamic and dynamic conditions of the atmosphere that are conducive to the multiple tornado occurrences were examined. Results show that large-value E-CAPE was concentrated in a relatively small area in the northeast quadrant relative to the Yagi center. Although a large fraction of the southeast quadrant of Yagi was characterized by moderate CAPE, marginal E-CAPE was obtained due to midlevel dry air intrusions. In the dynamic perspective, the northeast quadrant was also characterized by large low-level SRH. The tornado occurrences were generally located in the overlapping large-value region of SRH and E-CAPE, suggesting these two parameters may have contributed to the tornado potential in a complementary manner.

Considering that the low-level SRH is a useful variable for supercellular tornado prediction, the reason why the large-value SRH was concentrated in the northeast quadrant was further investigated. With the aid of the cylindrical coordinate form for the total helicity, the in-up-out profile of the low-level radial flow was found to be responsible for the large helicity in the northeast quadrant. Such a kinematic vertical structure resulted from the interactions between the typhoon circulation and the subtropical high and the east-moving midlevel trough. These two midlatitude synoptic systems were also responsible for the northeastward recurvature of Yagi. Although tornado outbreaks tend to occur in strong TCs as suggested by previous studies (e.g., McCaul, 1991; Verbout et al., 2007), the weak TCs that recurve to the northeast may also be likely to produce tornado outbreaks by the enhanced low-level shear and helicity in northeast quadrants as a result of the unique wind profile in that sector. The findings through the environmental analysis of the current tornado outbreak may help complement insights for our understanding of tornado risks within landfalling TCs, especially in coastal regions that are vulnerable to TC associated severe convective weather.

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CONFLICT OF INTEREST
The author declares no potential conflict of interest.

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